NASA/TM–2006–214139

Flight Dynamics Analysis Branch End of Fiscal Year 2005 Report

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

August 2006

Acknowledgments

The contents of this report are based on input generously supplied by members of the Mission Engineering and System Analysis (MESA) Division's Flight Dynamics Analysis Branch (FDAB) at NASA/Goddard Space Flight Center (GSFC).

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ABSTRACT

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2005. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based), spacecraft trajectory design and maneuver planning, attitude analysis, attitude determination and sensor calibration, and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

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1.0 INTRODUCTION

This is the seventh annual report produced by members of the Flight Dynamics Analysis Branch (FDAB) at the Goddard Space Flight Center (GSFC). The Branch is responsible for providing analytic expertise for trajectory and attitude systems. This includes dynamics and control analyses and simulations of space vehicles. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis, navigation, attitude determination, and controls analysis. The Branch also provides the expertise to support a wide range of flight dynamics services, such as spacecraft mission design, on-orbit sensor calibration, and launch/early orbit operations. An active technology development program is maintained, with special emphasis on developing new techniques and algorithms for autonomous orbit/attitude systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are the following:

- Attitude and trajectory analysis and control design
- Control/structure interaction analysis
- Mission (attitude and trajectory) planning
- Estimation techniques
- Vehicle autonomy
- Constellation analysis
- Flight dynamics model development

The FDAB also provides flight dynamics operations services through its Flight Dynamics Facility (FDF). This facility supported flight dynamics computations for more than 20 spacecraft in FY05. Operational services include orbit determination, acquisition data generation for the space and ground networks, tracking data evaluation, attitude determination and maneuver planning support. The FDF also supports Expendable Launch Vehicle (ELV) operations, International Space Station (ISS) orbit determination and Space Transportation System (STS) flight operations.

The FDAB is a branch in the Mission Engineering and Systems Analysis (MESA) Division (Code 590). The MESA division is responsible for providing strong mission-enabling leadership for a broad range of advanced science missions. In addition, many planned future missions will rely on highly integrated observatories in which the spacecraft functions and performance cannot be separated from the instrument and science functions and performance. The MESA division has the charter and the critical mass of people and skills to provide leadership in these areas. Within the division, the FDAB’s alliance with mission system engineers is a strong benefit to the infusion of flight dynamics technologies into new mission concepts, enabling the branch’s mission designers to meet the needs of mission formulation study teams.

This document follows an outline similar to one used in past annual reports. It summarizes the major activities and accomplishments performed by the FDAB in support of flight projects and technology development initiatives in Fiscal Year (FY) 2005. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year. The FDAB engineers that were involved in the various analysis activities within the Branch during FY2005 prepared this document. Where applicable, these staff members are identified and can be contacted for additional information on their respective projects. Project status and the projected dates for major events beyond FY05 are based on knowledge as of October 1, 2005.

Among the major highlights by engineers in the FDAB during FY2005 are:

- **STS-114 Return-to-Flight.** The Flight Dynamics Analysis Branch provided management oversight of the contractor support for the Space Transportation System (STS)-114 Return-to-Flight. NASA managers evaluated risk associated with the FDF and personnel training (after a contract change in January 2004), and ensured that these risks were mitigated. The launch on July 26th ended a 29-month stand-down following the Columbia accident in February 2003.
- **DART Mishap Investigation.** Branch personnel supported the Demonstration of Autonomous Rendezvous Technology (DART) Mishap Investigation Board (MIB) efforts for several months, requiring frequent travel to NASA Marshall Space Flight Center (MSFC). A senior flight dynamics engineer served on the MIB, and was provided technical assistance by several engineers within the Branch during this period.
- **HST Orbit Decay Analysis.** A major effort was made during the year to provide the Hubble Space Telescope (HST) Flight Project with long-term orbit decay analysis. This information was critical to the meetings held with Center management and the NASA Administrator to determine the fate of the Hubble Recovery Vehicle (HRV) development efforts.
- **AIAA/AAS Astrodynamics Specialist Conference.** The Flight Dynamics Analysis Branch was well represented at the American Institute of Aeronautics and Astronautics (AIAA)/American Astronautical Society (AAS) Astrodynamics Specialist Conference in Lake Tahoe, California on August 8–11, 2005. Branch personnel chaired some of the technical sessions, as well as presented a number of technical papers during the conference.
- **Development of On-Orbit Staging Concepts.** Senior engineers within the Branch provided a briefing to the Center Director and NASA Administrator for on-orbit staging mission concepts that are applicable to the Human Exploration and science initiatives. A considerable amount of analysis was performed to provide preliminary details concerning launch requirements, delta-v capabilities, fast transfer options, and the amount of mass that could be delivered to various destinations within the solar system.
- **Flight Project Support.** The Branch supported project-level reviews and mission readiness exercises during the year. Most notable are the following: peer reviews, integration and testing and numerous mission simulations for Space Technology 5 (ST5); the Project Critical Design Review for Space Technology 7 (ST7); the Lunar Reconnaissance Orbiter (LRO) Payload Kick-Off meeting to identify the instruments in January 2005, the System Requirements Review (SRR) in May 2005, and the Guidance, Navigation, and Control (GNC) Peer Review in September 2005; and the Solar Dynamics Observatory (SDO) Project Critical Design Review (CDR) in April 2005 and Ground System CDR in May 2005. ST5 is scheduled for launch in February 2006, SDO is in August 2008, LRO in October 2008, and ST7 in September 2009.
- **Hubble Robotic Servicing/Robotics Initiative.** Through the Hubble Robotic Servicing and Deorbit Mission (HRSDM) and continuing research that have followed the HRSDM cancellation, branch members worked to develop several advanced mission capabilities, including relative navigation design, autonomous rendezvous and capture, and dexterous robotic simulation for grapple and servicing. Work continues in relative navigation sensor data simulation and filter design, as well as robotics simulation augmented by hardware-in-the-loop contact-dynamics and machine-vision components.
- **Hubble Space Telescope Pointing Control Systems.** Branch personnel worked closely with Lockheed Martin and the HST Project on the development of three new pointing control algorithms, a two-gyro science mode, a one-gyro science mode, and zero-gyro safe mode. All of these new modes are intended to maximize the useful lifetime of this national asset until a future servicing mission.
- **NASA Engineering and Safety Center Guidance, Navigation, and Control Support.** The GNC Super-Problem Resolution Team (SPRT) of the NASA Engineering and Safety Center (NESC) had a very active year, with strong participation from members of the Flight Dynamics Analysis Branch. In addition to many other NESC activities, branch personnel participated in the Shuttle Recurring Anomaly Review and Orbiter Repair Maneuver Review Return-to-Flight (RTF) activities.

2.0 FLIGHT PROJECT SUPPORT

2.1 DEVELOPMENT MISSIONS

2.1.1 Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Mission

http://www-calipso.larc.nasa.gov/

The CALIPSO mission will use a lidar instrument with visible and infrared imagers to study how atmospheric aerosols effect Earth's weather, climate, and air quality. The CALIPSO spacecraft will launch as a dual payload with CloudSat, into a 705 km, Sun synchronous orbit, as part of the Earth Observing System (EOS) Afternoon Constellation that includes EOS-Aqua, EOS-Aura, CloudSat, Parasol, and the Orbiting Carbon Observatory (OCO). CALIPSO is a joint U.S. (NASA) and French (*Centre National d'Etudes Spatiales*/CNES) satellite mission with an expected 3 year lifetime.

FDAB is involved through technical oversight on a contract with A.I. Solutions, Inc, to provide mission design consultation to the NASA Langley Research Center (LaRC) who has overall program management. A majority of the work has been an effort to independently assess the ascent planning and execution as designed by CNES, who is responsible for spacecraft mission operations. This work has included developing the CALIPSO-CloudSat Coordinated Ascent Plan, which describes the coordinated but independently executed ascent of CALIPSO and CloudSat into their respective mission orbits while preventing risk to the rest of the Afternoon Constellation (AC). Simulations exercising the ascent were performed in September of 2005. The consultation has also included helping to define the requirements for turning off CALIPSO instruments during potential over flights of the Hubble Space Telescope.

The CALIPSO/CloudSat dual launch is currently scheduled for no earlier than November 2005.

[Technical contact: Michael Mesarch]

2.1.2 Earth Observing System (EOS) Constellation Management

The EOS Constellation Flight Dynamics (FD) analysis team supports both the EOS Morning and Afternoon Constellations. The Morning Constellation (MC), consisting of Terra, Landsat-7, EO-1, and *Satélite de Aplicationes Científícas* (SAC-C) flies in a sun-synchronous frozen orbit at 705 km, crossing the equator at ~10:30 am Mean Local Time (MLT). The AC flies a similar orbit, but crosses the equator at 1:30 pm MLT. The Aqua and Aura satellites of the AC were joined in December 2004, by the CNES Polarization and Anisotropy of Reflectances for Atmospheric Sciences couples with Observations from a Lidar (PARASOL) mission.

The FD team supported the exit of SAC-C from the MC. With most of its fuel depleted, SAC-C was unable to maintain its position within the MC. While it still could perform science, SAC-C needed to leave the vicinity of the constellation without endangering any of the other member missions. The FD team assisted the SAC-C team in analyzing the different options and provided recommendations to the Earth Science Mission Operations (ESMO) Project office and the Mission Operations Working Group (MOWG). Once the MC MOWG agreed to the option of raising SAC-C's orbit by approximately 2 km, so that it could safely pass over the other members, SAC-C successfully performed the maneuver sequence in July 2005. The FD team monitored the SAC-C maneuver sequence and position relative to

the MC satellites and verified the passage of SAC-C over Terra and LandSat-7. In early October 2005, SAC-C passed above the PARASOL and Aura satellites of the AC.

The PARASOL mission's entry into the AC was a critical event supported by the FD team. This mission tested the newly operational Constellation Coordination System (CCS). The FD team used CCS to analyze the ascent sequence and stationkeeping maneuvers of PARASOL. PARASOL was inserted between Aqua and Aura and is flying 120 s behind the Aqua satellite. While the MC satellites control their positions relative to the Worldwide Reference System-2 (WRS-2), the AC controls to the position of the lead satellite Aqua (which controls its position relative to WRS-2). This is known as phase control with Aqua, and allows the other Afternoon Satellites to fly relative to Aqua instead of to the WRS-2.

The different constellation control scheme for the AC required extensive analysis and modification of the CCS to ensure it could properly monitor both constellations. The CCS is used by the FD team to monitor the current and predicted location of each Morning and Afternoon Constellation satellite relative to the WRS-2. CCS had four releases in the past year to meet the new requirements. The FD team provided the mathematical and functional specifications and performed the acceptance testing of each release.

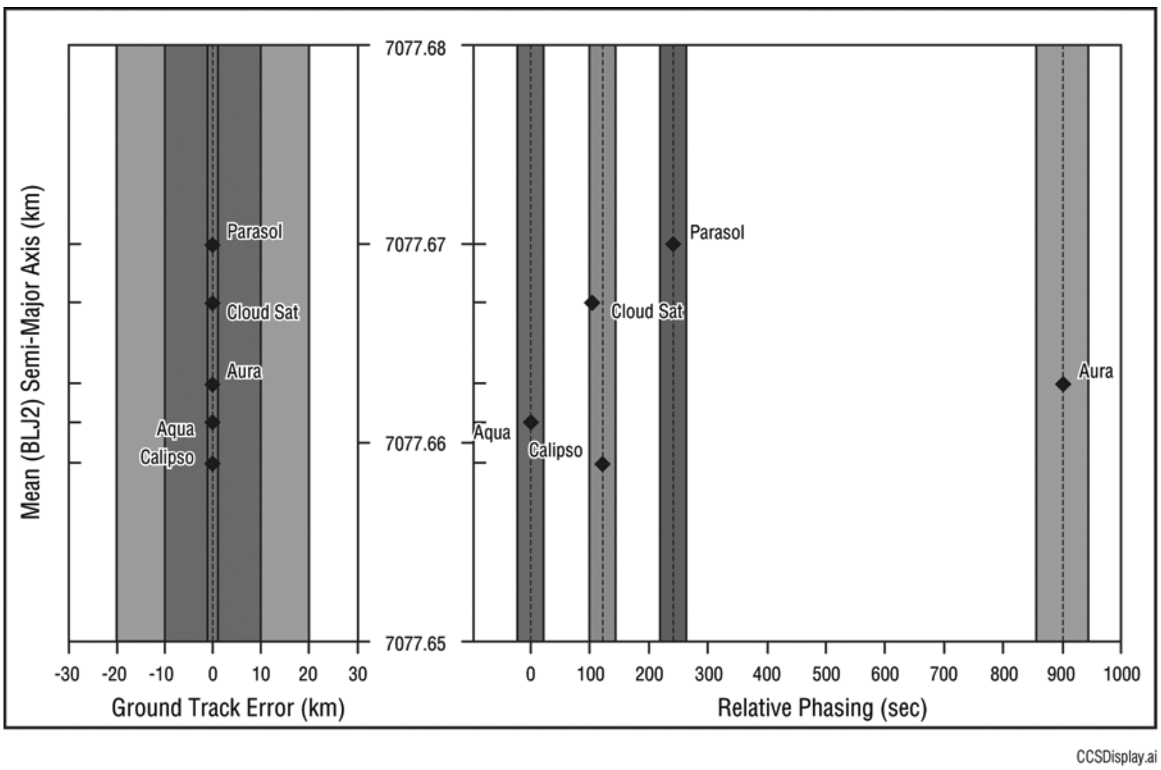

Figure 2-1. CCS Ground Track and Phasing Plot

The CCS has several unique displays to assist the analysts in monitoring the constellations; one of these is shown in figure 2-1, the CCS Ground Track and Phasing Plot for the Afternoon Constellation. Figure 2-1 illustrates the real-time position of all three operational satellites with respect to both their ground track requirements and their phasing requirements. Simulated positions of the CALIPSO and CloudSat missions, which will be joining the AC in late 2005, are also shown. The left side of the figure shows the ground track of each satellite relative to its control box, and the right side shows the phasing of the satellites with respect to Aqua. The colored bands represent the control box for each satellite. All three

satellites maintain a ± 10 km control box at the equator, which equates to ± 21.5 s phasing requirement. As can be seen, the AC satellites do not actually fly in a 'train' configuration (or a 'string of pearls'), as the MC does. This partially illustrates the challenges of the AC analysis.

[Technical contact: Karen Richon]

2.1.3 Gamma-Ray Large Area Telescope (GLAST)

http://glast.gsfc.nasa.gov/

GLAST is scheduled for launch in August 2007. It will be launched from the Eastern Range on a Delta-II Heavy launch vehicle and will nominally be inserted into a circular 565 km altitude orbit with an inclination of 28.5°. The spacecraft will fly with a pair of Viceroy Global Positioning System (GPS) receivers which will provide real-time orbit knowledge. The spacecraft attitude will operate in both a sky survey mode to map the gamma-ray field, and an inertial pointing mode to dwell on gamma-ray targets of interest.

FDAB personnel are actively working with launch services and Boeing personnel to provide the Trajectory Feasibility Analysis (TFA) for the Delta II, and the associated launch windows. During FY05, FDAB personnel provided mission analysis support to the project. The analysis support included an independent review of the GLAST deorbit plan and propellant budget. Using the Satellite Took Kit (STK)/Astrogator, the FDAB identified some incorrect assumptions in the original analysis, indicating that the nominal propellant budget was underestimated. Analysts also performed a parametric analysis for GLAST controlled reentry, analyzing five test cases: 1) nominal burn, 2) thrusters 5% hot, 3) thrusters 5% cold, 4) 5° attitude control error, and 5) burn start timing delay. The FDAB analysts also worked with Omitron engineers to provide a Tracking and Date Relay Satellite (TDRS) Ku-band scheduling analysis.

The FDAB is also involved with developments of the Flight Dynamics System (FDS) to provide operational orbit and attitude support. The FDS makes full use of Satellite Tool Kit (STK). The Orbit Determination Tool Kit (ODTK) is being used to filter/smooth the GPS point solutions telemetered from the Viceroy receiver. This is expected to improve the predictive orbit accuracy by roughly two orders of magnitude. Some in-flight Viceroy receiver data from the QuikScat mission were processed in order to validate the filter/smoothing approach. The results were presented at the STK Users Conference in October.

FDAB is also developing an Attitude Determination System (ADS) for GLAST, based on reuse of Mission Three-Axis Stabilized Spacecraft (MTASS) Software. This system will be delivered to the MOC in February 2006.

[Technical contact: Mark Woodard]

2.1.4 Global Precipitation Mission (GPM)

http://gpm.gsfc.nasa.gov/

GPM is both a spacecraft mission designed to collect information on precipitation on a global scale and a program intending to collect and process similar data from other spacecraft missions in order to better understand the Earth's water lifecycle. Original plans called for the Core Spacecraft to be built in-house at GSFC, but because of programmatic limitations, NASA Headquarters instructed GPM to pursue the

option of procuring the spacecraft through Goddard's Rapid Spacecraft Development Office (RSDO). While competing vendors continue to conduct this study, FDAB personnel have been asked to refine previous analyses in the following three areas: core spacecraft orbit control box size, optimization of potential constellation spacecraft coverage (including helping project scientists identify a nominal coverage figure of merit), and a ground site validation study.

Starting with a reference orbit of 400 km (circular) and a 65° inclination, FDAB personnel have been tasked to maximize the global coverage of the two precipitation radars and the microwave imager onboard the core spacecraft, minimize altitude variation over the course of an orbit, and minimize altitude variations over any given latitude. Means of maintaining a nominal orbit while minimizing the impact on science data collection include both one and two-burn solutions.

Optimization of the GPM constellation, which is still an unidentified entity but may consist of 6–12 radiometer-carrying spacecraft, has proven to be a daunting task, but one for which FDAB personnel have offered a number of options. Depending on how the constellation coverage is to be defined (coverage figure of merit)—and there have been a number of options studied—a fleet of spacecraft, some with already fixed orbits and some that can be varied, would be tuned to achieve that goal. FDAB personnel have been continuing to help project scientists define the optimal figure of merit and refining approaches for achieving the overall objective of maximizing science data collection.

Lastly, part of the GPM program includes ground sites that will serve to validate measurements made by the core spacecraft science instruments. FDAB personnel have conducted studies over the past year to help select desirable locations for one or more of these sites.

[Technical contact: Chad Mendelsohn]

2.1.5 Geostationary Operational Environmental Satellite (GOES) – N

The GOES-N spacecraft, which is the first in the GOES-(N–P) series, was scheduled for launch early in the second quarter of 2005. A host of spacecraft and launch vehicle problems, however, have delayed the launch until no earlier than October 2005. The GSFC GOES-N Flight Dynamics Team prepared to support the GOES Project as consultants and validation analysts during the prelaunch and orbit circularization period with Boeing Satellite Systems (BSS) as prime for Flight Dynamics operations. GSFC FDF was given one prime assignment during the early orbit period involving the generation of Collision Avoidance data for USSTRATCOM to analyze. Following preparation of a BSS orbit maneuver plan, the GSFC FDF will prepare ephemeredes reflecting the maneuver. These would be sent to USSTRATCOM and examined for potential close approaches with other spacecraft or orbiting debris. The FDF at GSFC will also perform backup orbit determination and acquisition data support during the orbit circularization phase of GOES-N.

Following arrival on-station, the GSFC Flight Dynamics Team will provide prime support to the GOES-N Mission Operations Support Team (MOST) during the checkout of spacecraft subsystems and activation of the satellite's Image Navigation and Registration system. The role of the GSFC FDF includes precision orbit determination, acquisition data generation and delivery and validation of station keeping maneuvers planned and calibrated by the GOES-N ground system at NOAA's Suitland Operations Control Center.

[Technical contact: Robert DeFazio]

2.1.6 Hubble Robotic Vehicle (HRV)

In the wake of losing Columbia and the subsequent grounding of the Space Shuttle fleet, the Hubble Robot Servicing and De-orbit Mission (HRSDM) was born. An aging Hubble Space Telescope (HST) required servicing and a safe deorbit at its end-of-life. The HRSDM was an ambitious solution to the problem of preserving one of the Agency’s most prominent assets, whose onboard batteries are predicted to degrade below a functional level as early as 2008. The proposed method of recovery involved an HRV launched on an Expendable Launch Vehicle (ELV). The HRV would rendezvous with HST, perform the necessary repairs, and later steer HST into a controlled reentry.

The HRV design presented flight dynamics with many unique challenges in the field of autonomous rendezvous and capture (AR&C), robotics, and remote sensing. The mission plan included an on-orbit rendezvous using ground-based orbit determination methods augmented by onboard GPS/INS instruments and multiple lidar sensors on the HRV. Naasz discusses the flight dynamics design of the close proximity navigation, including lighting and power constraint optimization, in his 2005 Flight Mechanics Symposium paper, “*Safety Ellipse Motion with Coarse Sun Angle Optimization.*”

For the HRV mission, a co-elliptic orbit was selected to be roughly 150×75 m, which was distance enough to provide a margin on navigation errors, but close enough for both the Neptec Laser Camera System and a Lockheed-Martin camera-based image-matching system called the Natural Feature Image Recognition (NFIR) instruments to provide an estimate of the relative attitude (pose) of HST. At distances of 10 m and less, a redundant set of distance measurements to berthing targets is provided by the Enhanced Auto-Track Computer Vision System (EACVS). Both NFIR and EACVS are operational during capture and berthing operations and are crucial for closed-loop vehicle control.

The mission design required provisions for docking with both a cooperative HST—commanded to a favorable attitude—and the possibility of a defunct and tumbling HST (postbattery failure). In the latter case, the servicing portion of the mission would no longer be relevant, but the requirement for a controlled deorbit would remain. Based on analysis provided by the GSFC Flight Dynamics and Analysis Branch, the maximum passive vehicle rates for HST were determined to be less than $\pm 0.22° \ s^{-1}$ per axis, with no preferred orientation or stable axis of rotation. This contingency necessitated an accurate, remote, and real-time estimate of the target's “tumble” rate in order to predict the orientation of a “docking axis” along which the HRV could approach HST. A number of advanced control and estimation methods were examined by GSFC in conjunction with Draper Labs, the HRV navigation system designers. A comparison of potential filter performances was presented in the AIAA paper, “*Hubble Space Telescope Angular Velocity Estimation During the Robotic Servicing Mission*,” by Thienel, Queen, VanEepoel, and Sanner.

The final approach to HST along a prescribed docking axis (or cone) included way points at 30 and 10 m separation requiring authority-to-proceed commands from the ground. The final hold point was a tantalizingly close 1 m off the aft bulkhead. Capture of the HST grapple fixtures occurs via a 39 ft, six-jointed robotic Grapple Arm (GA) (primary mode), or a direct thruster-propelled docking onto the HST aft berthing pins (contingency mode). New technology used for this mission segment includes a closed-loop vision system that guided the GA from a predefined “ready-to-capture” position to snaring of the HST grapple fixture. After a successful snare, the GA would then rigidize the connection and maneuver the HRV the final distance to a “soft” capture of the HST aft bulkhead berthing pins. GSFC Flight Dynamics contributions to the design of this phase included high-fidelity simulation of the dual vehicle dynamics and control systems. To facilitate analysis, GSFC developed a unique version of the multi-body dynamics and GA joint controller. The dynamics solution was specifically optimized for a serial chain of revolute joints, and successfully implemented in the HRV real-time simulator. The details of the

formulation are contained in a 2005 Flight Mechanics Symposium paper, "*Momentum-Based Dynamics for Spacecraft with Chained Revolute Appendages*," by Queen, London, and Gonzalez.

The longest portion of the mission involves the teleassisted servicing of HST. This is accomplished by attaching an additional robotic appendage onto the GA. This robot (initially stowed in the aft bulkhead of HRV) was termed the Dexterous Robot (DR) and utilized the existing Special Purpose Dexterous Manipulator (SPDM) unit, which had been built for the International Space Station (ISS). Its configuration includes two seven degree-of-freedom appendages and a central torso that connects to the GA via a grapple fixture. Four servicing tasks were scheduled: umbilical connection/battery augmentation, gyro replacement, COS replacement, and Wide Field Camera 3 installation. The FDAB's role in the servicing operations included dynamic simulation of the appendage motion for timeline design, coupled vehicle/arm control analysis, lighting condition and camera-view determination, as well as structural load assessment caused by contact dynamics.

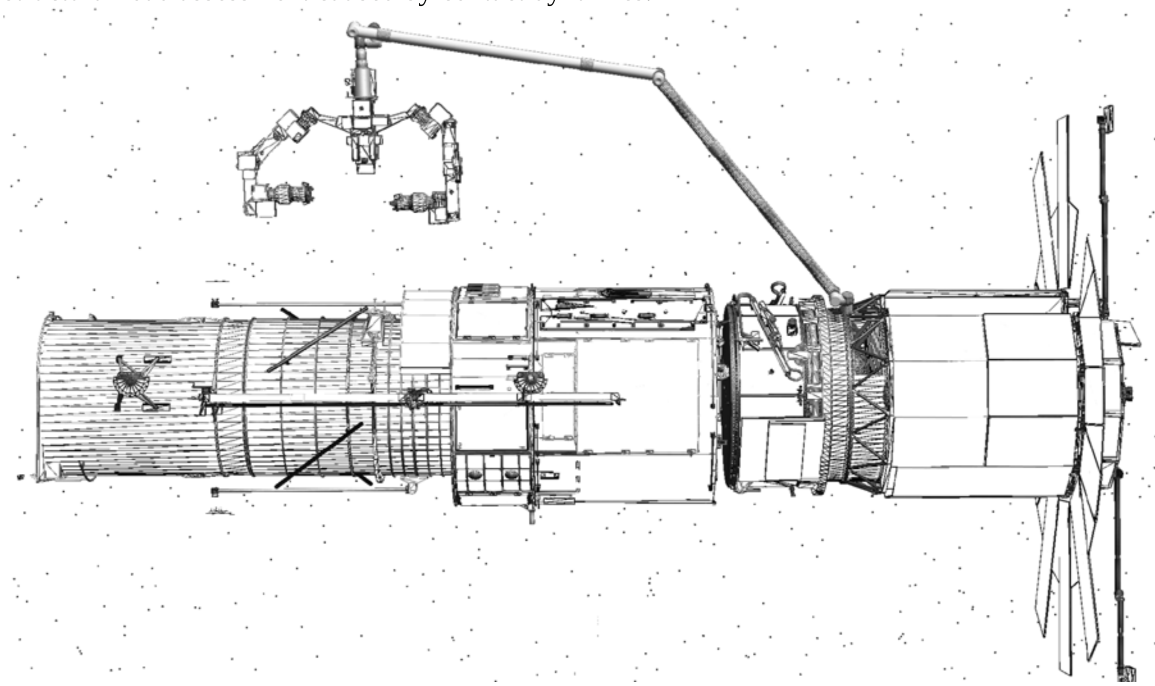

Figure 2-2. HRV Servicing Concept

Upon completion of the servicing tasks (assuming a functional HST), the HRV provides an orbit re-boost to the HST stack and then divides into two independent vehicles. An Ejection Module (EM)—containing the robot arms, rendezvous AR&C systems, and the discarded HST instruments—and a Deorbit Module (DM) remains attached to HST and performs the final re-entry maneuvers at end-of-life.

With the successful return to flight of the Space Transport System, the Agency is now favoring a Shuttle-based fourth servicing mission (SM4) in lieu of HRSDM. The HRSDM project has been de-scoped to a Shuttle-based technology demonstration of the relative navigation sensors and a robotics research initiative—two technological arenas exposed as relatively high risk during the HRSDM Preliminary Design Review.

[Technical contact: Steve Queen]

2.1.7 James Webb Space Telescope (JWST)

http://www.jwst.nasa.gov/

The JWST Project organized two working groups to solve two significant technical problems: Orbit Trade Working Group (OTWG) and the Momentum Management Working Group (MMWG).

The OTWG refined the mission orbit constraints to include stray light violations and launch window constraints. The OTWG was made up of FDAB, Northrop Grumman Space Technology, and A.I. solutions, Inc. The results of the OTWG were a complete set of mission orbit solutions that meet all requirements. Each solution consists of an entire JWST orbit ephemeris from spacecraft separation through 10 years in the mission orbit. The resulting launch window is shown in Figure 2-3. The unhatched gray region is the acceptable launch window.

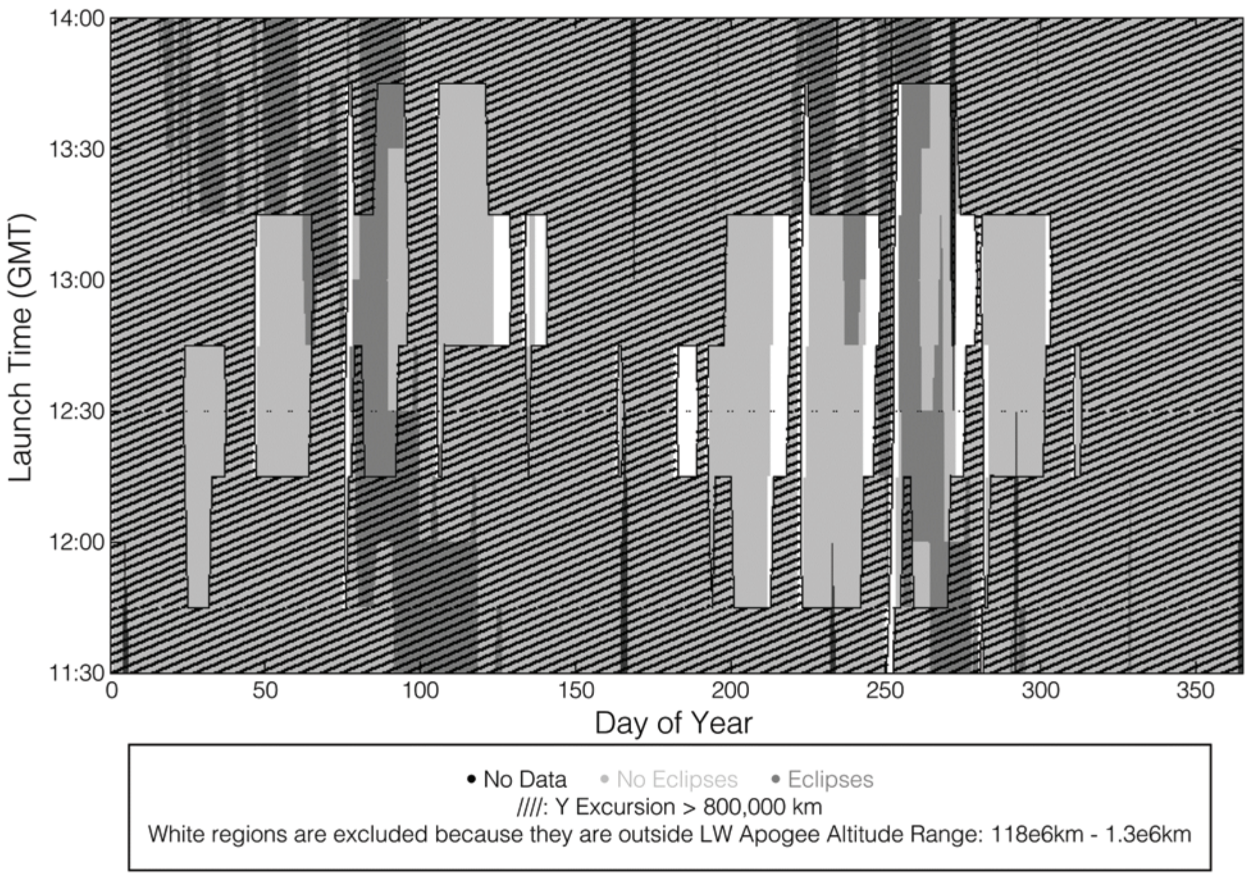

Figure 2-3. JWST Launch Window

The MMWG investigated solutions to the observatory momentum management issues. Momentum unloading is unbalanced on JWST and imparts a ΔV perturbation on the orbit. This perturbation affects both orbit determination and stationkeeping ΔV. The MMWG addressed the issue with several changes to design and concept of operations. Combined, changes in wheel size, speed and operating range, an optimized stationkeeping strategy, and additional yaw thrusters, meet constraints imparted from orbit determination, stationkeeping ΔV, and the Science Operations Center.

[Technical contact: Mark Beckman]

2.1.8 Lunar Reconnaissance Orbiter (LRO)

http://lunar.gsfc.nasa.gov/

The Lunar Reconnaissance Orbiter (LRO) mission is the first of a series of exploration spacecraft aimed at eventually returning manned presence to the Moon as part of the Robotic Lunar Exploration Program (RLEP). The main objectives of the LRO mission are to characterize the lunar environment and how to mitigate the affects of this environment on the future manned missions to the lunar surface. FDAB has played a significant role in the early mission phases.

The LRO mission is currently scheduled to be launched in late 2008 aboard a Delta-II heavy ELV. The Delta-II will put the LRO spacecraft into a direct insertion trajectory to the Moon. The cislunar trajectory will take approximately four days before several insertion burns will be employed to insert the spacecraft into the instrument commissioning orbit. A quasi-frozen orbit will be used for the instrument commissioning phase. This frozen orbit is a 30 x 216 km altitude with a 90° inclination. While in the frozen orbit, altitude will be maintained within a very narrow band and will not require stationkeeping to maintain. After two months, LRO will be transferred into the 50 km polar mission orbit. During the mission orbit, the LRO spacecraft will be three-axis controlled in a lunar nadir pointing attitude. LRO will remain in this lunar orbit for a period of one year. LRO will use an optimized stationkeeping strategy that repeats every lunar sidereal period. This stationkeeping strategy minimizes ΔV costs while maintaining burns within view of ground stations, controlling periselene, and limiting altitude variations. Orbit determination will be based on 30 min per orbit of S-band range and Doppler data. The Lunar Orbiter Laser Altimeter (LOLA) instrument team will provide updated lunar gravity modeling about three months into the mission orbit. The expected improvement in gravity model will improve orbit determination accuracy by about an order of magnitude.

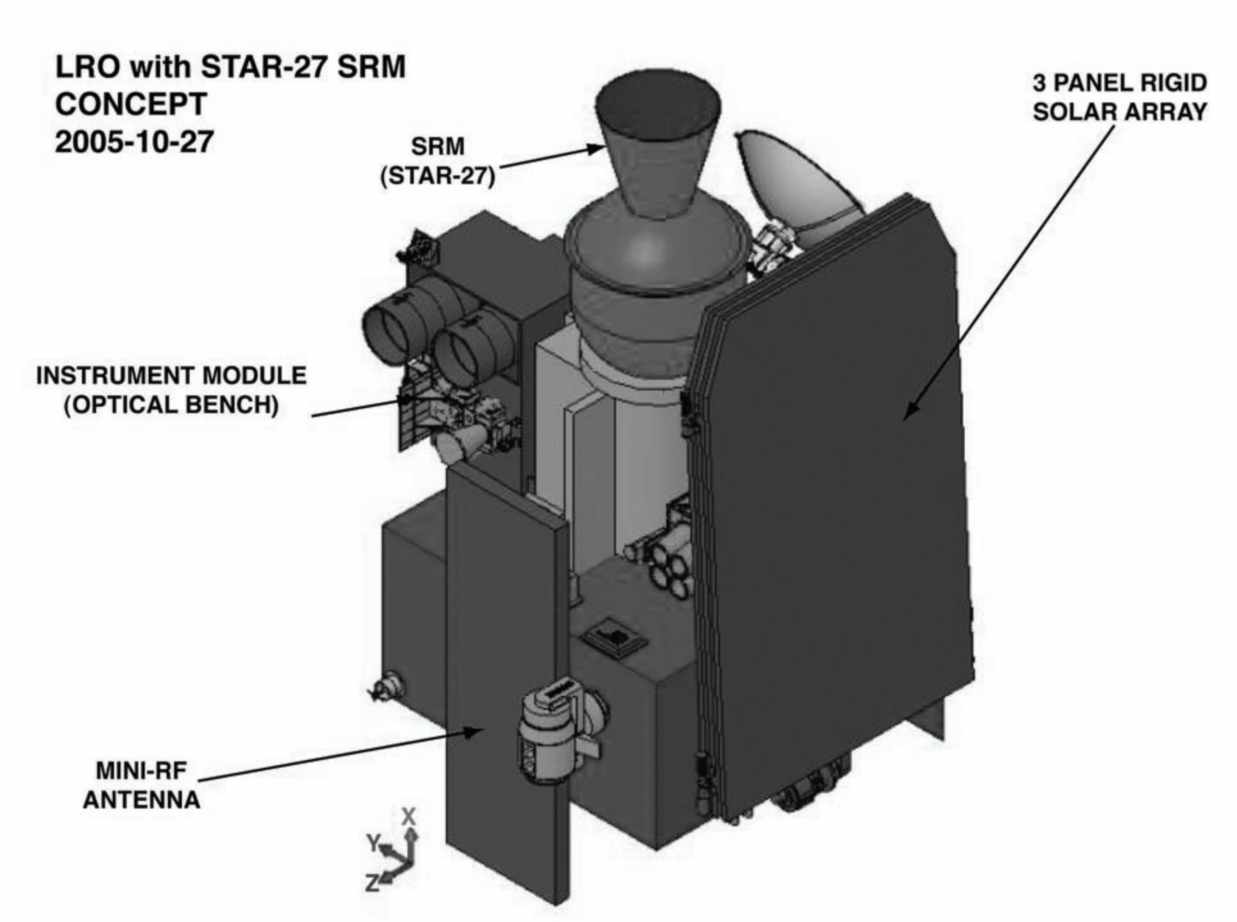

Figure 2-4. LRO Spacecraft Design

An Attitude Control System (ACS) team from FDAB has, during the past year, been contracted by the LRO Project Office to support the early concept, requirement definition, and design phases. The ACS team main activities during these early phases were to support the Project and other subsystems by providing analysis, and investigating different configurations and concepts. These ACS team trade studies included reaction wheel sizing, thruster sizing and locations, hardware redundancy needs, mode definitions and stability analysis, and means to put the spacecraft into a safe pointing configuration in the event of an anomaly. A High Fidelity (HiFi) simulation tool is used to test all algorithms against defined requirements, concepts, and identified anomalies. The HiFi dynamics simulator makes use of the MathWorks Matlab/Simulink. Future work will be to use the HiFi simulator to perform Monte Carlo simulations to test algorithms against varying performance parameters.

The LRO Project successfully completed its Systems Requirements Review (SRR) on August 16–18, 2005. A Guidance Navigation, and Control (GNC) Peer Review was held on September 29, 2005 to review preliminary design and analysis. The Mission Preliminary Design Review (PDR) is scheduled for November 14, 2005.

[Technical contacts: Mark Beckman and Joe Garrick]

2.1.9 Magnetospheric Multiscale (MMS) Mission

http://stp.gsfc.nasa.gov/missions/mms/mms.htm

MMS is part of the Sun–Earth Connection program, a four-spacecraft solar-terrestrial probe designed to study magnetic reconnection, charged particle acceleration, and turbulence in the key boundary regions of the Earth's magnetosphere. A mission of this type has never been developed nor operated at GSFC before and presents many challenges to both pre and post-launch support.

MMS development is in Phase A, with an in-house Phase A Observatory Study just underway. Since May 2005, the emphasis has been on defining mission requirements, on developing software to find mission scenarios that satisfy those requirements, and on identifying potential problems that result from the requirements. The software has been divided into two broad categories with development ongoing for both. One category is concerned with the reference trajectory—the trajectory used when discussing the four satellites as a single entity. The other is concerned with the individual satellites and their motion relative to the reference trajectory and each other, also called formation flying. Additional input was provided to the project to support the Detailed Mission Requirements and the Observatory Requirements, meetings with and presentations to Project management, the Project scientist, and SwRI, developing operations concepts for this complex mission, and participation in readiness for demonstrations of internal technology development to support navigation for formation flying.

[Technical contact: Cheryl Gramling]

Mission Design

The MMS mission consists of three main science phases, each a highly eccentric high Earth orbit, plus a double lunar swing-by phase. After early orbit, phase 0, MMS will be in phase I, a 1.2 Earth Radii (Re) by 12 Re orbit with inclination of 28.5°. For phase II, the apogee will be raised incrementally to 25 Re and inclination changed to 10°. After a double lunar swing-by to raise perigee to 12 Re, the phase III apogee will be approximately 31 Re. Relative separations among the four spacecraft are incrementally varied from 1000 km to 10 km.

The reference trajectory software has been developed for the early orbit, phase 0, through phase I. Additional effort has centered on defining mission design requirements in concert with the science team and producing and presenting Project- requested analyses results to the Project and science teams.

There are numerous challenges to provide end-to-end support of a formation flying mission. These include the development of the operational strategy for separation of the individual spacecraft from the stack, to reconfiguring the formation for a new mission phase. The FDAB formation flying support had been focused on two primary areas. The first is developing baseline formations for each phase of the MMS mission. A direct method was developed to provide optimal formation geometry based on a mission specific performance metric. By using powerful orbit design methods, excellent formation evolution for all mission phases can now be provided. Figure 2-5 shows the MMS performance metric over one orbit for an optimized formation. The performance metric is always between 0 and 1, where 1 is the best possible configuration. The figure indicates that near apogee, a near-regular tetrahedron is possible.

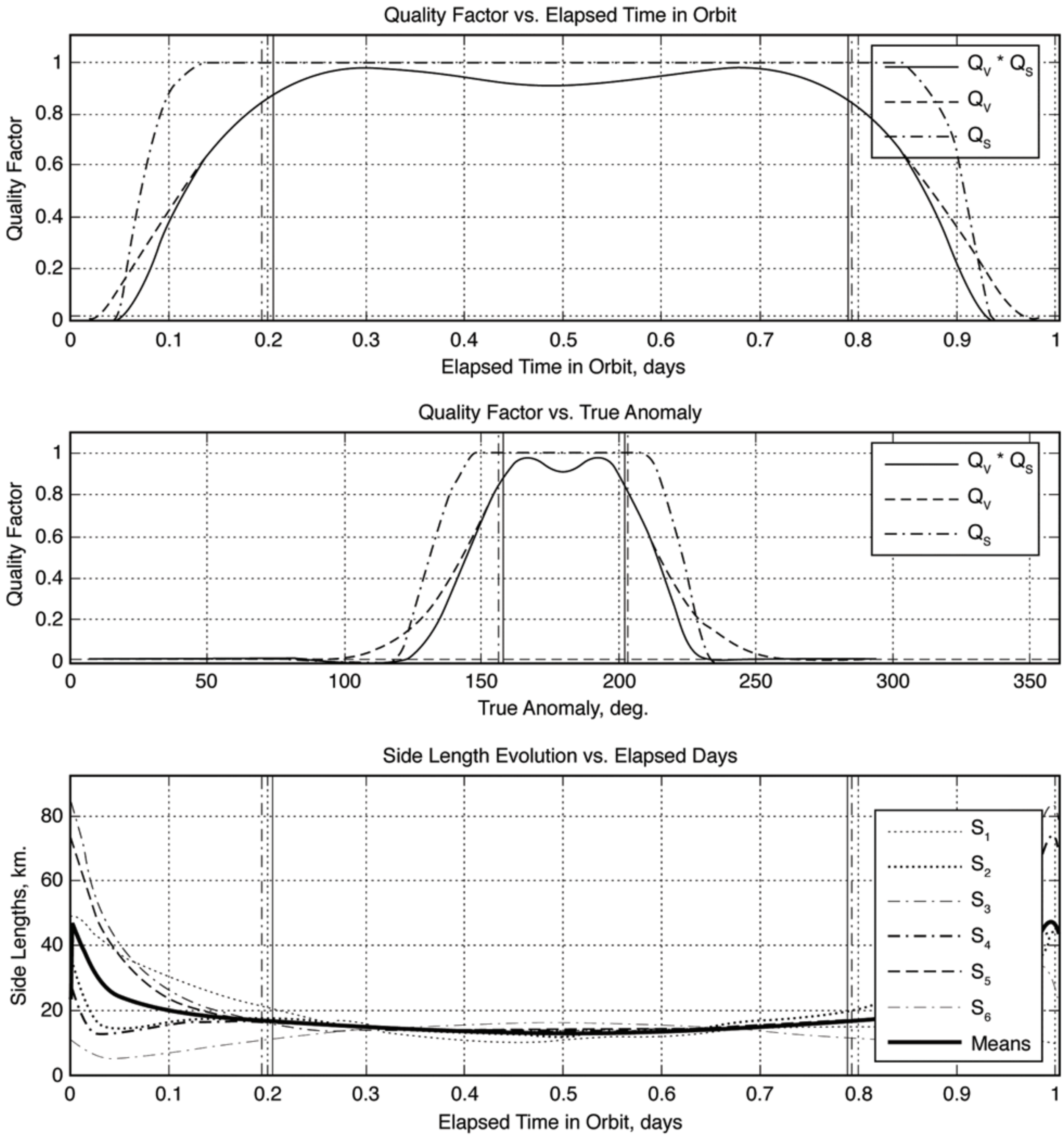

Figure 2-5. MMS Performance Metric

The second area of support has been in error analysis. It is desirable not to interrupt science operations to perform formation-keeping maneuvers unless absolutely necessary; however, there are numerous error sources that influence the stability of the MMS formation. The effects of navigation and thrust errors have been incorporated and used to determine the expected maneuver frequency for phase I, 10 km tetrahedrons. The effort continues by investigating other formation sizes and mission phases.

[Technical contacts: Charles Petruzzo, and Steven Hughes]

Navigation and Orbit Determination Analysis

Efforts this year centered on assisting the in-house development of the Interspacecraft Ranging and Alarm System (IRAS) to reach Technology Readiness Level (TRL) 5. After the Science Team Kickoff, navigation analysis began to ensure the formation flying requirements of the newly defined mission can be met with the baseline ground support.

[Technical contact: Russell Carpenter]

Attitude Control System

Analyses centered on quantifying the orbit maneuver errors imposed by spacecraft uncertainties and system errors, such as the thrust magnitude and direction uncertainties, attitude and spin-phase knowledge, unknown nutation angles, and center-of-gravity uncertainties. All have shown significant contributions to the maneuver errors. Furthermore, a new maneuver strategy has been suggested for MMS maneuvers, enabling the MMS spacecraft to maneuver accurately in space while not disturbing the spinning motion.

[Technical contact: Dean Tsai]

2.1.10 National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP)

http://jointmission.gsfc.nasa.gov/index.html

NPOESS NPP is a joint mission involving the National Aeronautics and Space Administrations (NASA) and the NPOESS Integrated Program Office (IPO). Specific information regarding the mission goals and cooperative interagency effort may be found at the Web site given above.

Flight Dynamics Analysis Branch personnel were tasked by the GSFC NPP Project management to review the mission operations plan for comments on the planned approach for NPP postlaunch support. FDAB analysts have provided NPP documentation review comments/questions, have attended Mission Operations Working Group (MOWG) meetings, and have supported other special topic meetings at the spacecraft manufacturing facility. They have also provided independent validation of the spacecraft manufacturer's reentry analysis and generated other reports regarding typical FDAB mission support functions. One of the reports noted that independent validation of the onboard attitude determination could be beneficial to the NPP mission goals. This capability would be implemented using the institutional, ground-based FDAB Attitude Determination System (ADS), with some mission-specific modifications. Sensor calibration capabilities for many current attitude sensors already exist in the FDAB ADS and these could supplement the attitude sensor calibration activities planned by the spacecraft manufacturer. These ground-based, ADS capabilities may be developed and used for NPP pending Project approval and funding.

[Technical contact: David Tracewell]

2.1.11 Solar Dynamics Observatory (SDO)

http://sdo.gsfc.nasa.gov

The SDO is scheduled for launch in the last half of calendar year 2008. In 2005, the SDO Mission Team has successfully negotiated the Critical Design Reviews (CDRs) for the spacecraft and all associated subsystems. The Flight Dynamics (FD) Team's work on the critical design was reviewed four times between mid-January and mid-May 2005. In those four reviews, the Review Teams or those attending, directed a total of nine Requests for Action (RFA) on the Flight Dynamics Subsystem (FDS) design. All RFAs were quickly and thoroughly answered to the satisfaction of the originators.

Once the design was approved for the FDS, implementation plans were outlined to meet software releases in June 2006, January 2007, and October 2007. Much of the software in the FDS design is Commercial Off-the-Shelf (COTS) or COTS-based with major software development or significant modifications involving less than half of the software tools in the FDS. Work on the Release 1 software delivery began during the last quarter of FY05 with acceptance testing of this release scheduled for March 2006. A delivery was made in August 2005 of FDS products required to test the SDO Mission Planning System interface with the FDS.

The duties and responsibilities of the SDO FD Team include the aforementioned development and testing of the FDS, as well as mission analysis support for the Project and spacecraft subsystems. This analysis has included: a study of available launch windows in the third quarter of calendar 2008, generation of an orbit circularization profile following launch on an Atlas-V (401) launch vehicle, development of several additional FDS products requested by the SDO Science Team, and a detailed plan for calibration of the SDO High Gain Antennas. All FDS analyses are well documented and compiled in a compendium at the end of each calendar year.

The SDO FD Team is also responsible for writing and updating documents covering Flight Dynamics requirements, design, interface control, and acceptance test plans. At the end of FY05, all these documents were baselined and are being kept up to date.

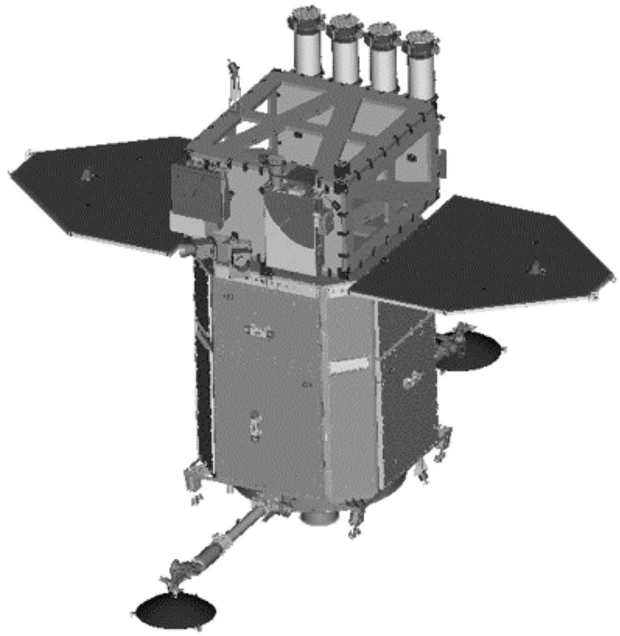

Figure 2-6. The Solar Dynamics Observatory

The SDO Attitude Control System (ACS) Analysis Team has also completed major design activities for the on-board ACS and the ground-based HiFi Simulink simulation. The team has now shifted its main focus to assisting in the development and testing of flight software. In particular, the Analysis Team is responsible for creating Simulink models of the main processor control modes from which flight software will be automatically generated using MathWorks' Real-Time Workshop. The team is also actively involved in Failure Detection and Correction design for the mission and in development of the High Gain Antenna (HGA) pointing algorithm.

The Analysis Team conducted two peer reviews in addition to the spacecraft-level CDR: a Peer Analysis Review to examine analysis methods more closely and to present answers to some RFAs, and a tabletop HiFi Review to gather guidance for the continued development and use of the HiFi after CDR. A trade study on the Safehold design was presented as part of the Peer Analysis Review; the result of the trade study was to use inertial reference units during eclipses in Safehold mode to avoid excessive drift while the Sun is unobservable. Another trade study determined how to best handle use of the integrators in the Proportional Integral Derivative (PID) controllers for the fine-pointing modes. The integrators will be frozen when attitude or angular rates exceed specified limits, effectively preventing integrator action during either commanded slews or transient errors in attitude.

During the period of conducting additional reviews and responding to RFAs after the January CDR, the Analysis Team also engaged in several detailed analyses. Modeling of the effects of sensor errors and noise sources on high-frequency jitter during science observations was thoroughly investigated, resulting in increased confidence that the ACS and the instrument stabilization systems will be able to work in concert to successfully eliminate motions that blur or distort the science images. Propellant slosh analysis based on final design of the propellant management device was completed. This analysis showed that the

existing ACS design, with its initial settling burn to avoid excessive shock from the main engine, will be sufficient to protect the spacecraft from large attitude transients during the thruster maneuvers that will establish and maintain the geosynchronous orbit so important to continuous downlink of the solar image data.

Details of these analyses and trade studies will be available in papers being presented at the Goddard Flight Mechanics Symposium in October 2005, and likely in future publications as well.

[Technical contacts: Robert L. DeFazio and Scott R. Starin]

2.1.12 Space Technology 5 (ST5)

http://st5.gsfc.nasa.gov/

Space Technology 5 (ST5) is a mission in the New Millennium Program and NASA’s first experiment in the design of miniaturized satellite constellations. ST5 is scheduled to launch on February 28, 2006 from Vandenberg Air Force base aboard a Pegasus XL launch vehicle. The mission will last 90 days. During this time the constellation of three spin-stabilized spacecraft will validate new technology for spaceflight while demonstrating formation flying capabilities. Technologies to be validated include a miniature cold gas thruster, x-band transponder, flexible interconnects, variable-emissivity coatings, ultra lower-power logic, autonomous constellation management ground software, as well as, various technology improvements embedded in the spacecraft itself.

The ST5 GNC team has developed a maneuver plan to validate onboard thrusters and deploy the constellation to two predefined formations over the 90 day mission. This plan will obviate the need to precess the attitude of each spacecraft before and after each orbit maneuver, which will simplify operational support and ultimately save propulsion.

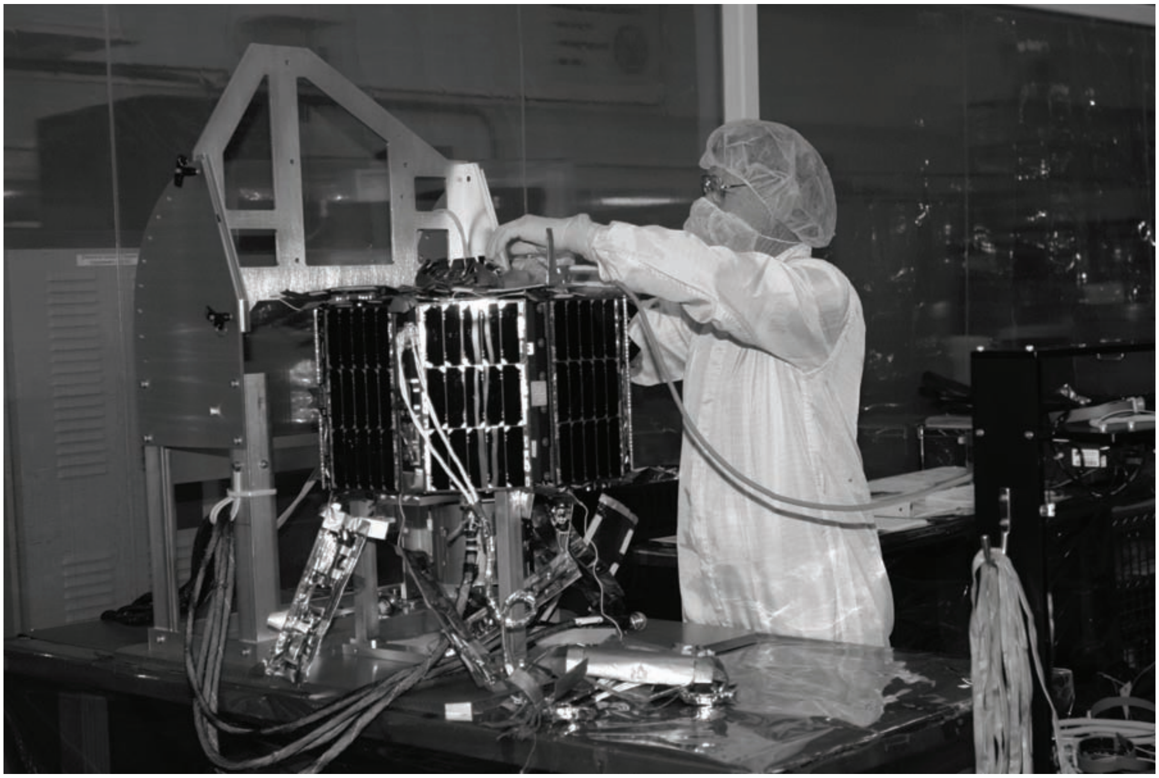

Figure 2-7. Technician Preparing One of the Three ST5 Spacecraft

In 2005, the following reviews were supported by the ST5 GNC team:

- Software Guideline Compliance Review, April 4, 2005
- Constellation Operations Review, May 17, 2005
- Flight Dynamics/Mission Operations Peer Review, June 4, 2005

The ST5 Code 595 team reorganized staff in support of operations planning activities. The command authorization and planning of maneuvers was assumed by the Maneuver Operations Team (ST5 MOT). The generation of operations flight dynamics products including attitude determination and estimation was assumed by the Attitude Determination System Team (ST5 ADS). The evaluation of tracking data and generation of orbit determination for ST5 was assumed by the ST5 Flight Dynamics Facility Team.

Mission simulations of the constellation have been conducted with increasing success in refining the maneuver planning process. Staffing schedules, operational procedures, independent validation and verification of maneuver principal algorithms, and maneuver team training in the operational environment have all progressed on schedule to support the 2006 launch. Important simulation milestones include:

- Launch and Early Orbit simulation to validate timeline and general support procedures.
- Attitude maneuver simulations to simulate command generation and authorization procedures with the Flight Operations Team (ST5 FOT).
- Orbit maneuver simulations to simulate command generation and authorization procedures with the ST5 FOT.
- Extended 12-day Launch and Early Orbit simulation to validate staffing plan and identify logistic bottlenecks and issues in support of three independent spacecraft and five maneuvers in 12 days.

[Technical contact: Marco Concha, Mark Woodard]

2.1.13 Space Technology 7 (ST7) Disturbance Reduction System (DRS)

http://nmp.jpl.nasa.gov/st7/

The Space Technology 7 (ST7) DRS is a project within the New Millennium Program, being managed by the Jet Propulsion Laboratory (JPL), with an original mission objective to test two advanced technologies: Gravitational Reference Sensors (GRSs), developed by Stanford University and Colloidal MicroNewton Thrusters (CMNTs), developed by the Busek Co. of Natick, Massachusetts. In the original mission, the GSFC Flight Dynamics Analysis Branch (FDAB) was responsible for developing the Dynamic Control System (DCS), the six-degree of freedom drag-free control system for the mission. ST7 is scheduled to fly as an instrument package aboard the ESA SMART-2: Laser Interferometer Space Antenna (LISA) Pathfinder (LPF) spacecraft in 2009, to an orbit around the Sun–Earth L1 Lagrange point.

During the last year, a lot has happened programmatically with ST7. The mission has been descoped, rescoped, and descoped a second time. In the final descoped mission, the GRS has been removed and the mission, now known as a Precision Flight Experiment, will involve the validation of a single technology, the CMNTs, along with the drag-free control laws. The drag-free control system being developed by GSFC will instead use the European GRS, being developed as part of a similar instrument package known as the LISA Test Package (LTP) to fly on LPF. This change also increased the scope of responsibilities for GSFC; in the original mission, Stanford was responsible for the GRS test mass control system, while in the descoped mission which GSFC is responsible for that. The GSFC responsibilities for ST7 now consist of the development of the DCS, that controls the spacecraft position and attitude to establish drag-free motion of the test masses; development of a GRS control system to be used in conjunction with the LTP GRS; development of a full nonlinear high fidelity dynamic model of the spacecraft and test masses; and generation of flight code for the DCS and GRS.

During FY 2005, the FDAB accomplishments include:

- Completed software acceptance testing.
- Delivered final flight software to JPL.
- Supported re-planning activities associated with descoping, rescoping, and descoping the mission.
- Completed feasibility study on using the LTP GRS.
- Completed feasibility study on accommodating higher thruster noise.
- Supported ST7 Project-Level Critical Design Review.
- Presented paper at the 18th International Symposium on Space Flight Dynamics, in Munich, Germany.

[Technical contact: Oscar Hsu]

2.1.14 Solar TErrestrial RElations Observatory (STEREO) Mission

http://stereo.gsfc.nasa.gov/

The STEREO program utilizes two spacecraft to provide stereoscopic imaging of the Sun and the Sun’s Coronal Mass Ejections (CMEs). STEREO will achieve these goals by placing one spacecraft in an orbit leading the Earth and the other spacecraft in an orbit lagging the Earth by means of a pair of lunar gravity assists. The two STEREO spacecraft will be launched into phasing orbits where maneuvers will be used to target the lunar gravity assists. This is similar to what was done for the Wilkinson Microwave Anisotropy Probe (WMAP). The spacecraft are being built by the Johns Hopkins University’s Applied Physics Lab (APL). APL is also responsible for the mission design. The Flight Dynamics Analysis

Branch is supporting the STEREO project by performing the orbit determination for the two STEREO spacecraft.

Activities for FY05 have primarily been in the area of testing software modifications necessary for launch. The FDF will receive X-band, 2-way tracking data (range and Doppler) with ramped frequencies from the 34m subnet. Software changes to the Goddard Trajectory Determination System (GTDS) were needed in order to be able to process the tracking data using the ramped frequencies. The changes have been made and ongoing testing continues, using data from operational spacecraft (e.g., Stardust and Deep Impact). In addition to the GTDS modifications, a software tool to transform the STEREO momentum unload maneuvers into a thrust table for inclusion into GTDS has also been undertaken. This software has been coded and is currently in testing.

Documentation efforts have included updating the FDF/STEREO Mission Operations Center Interface Control Document (ICD) and finalizing the first version of the STEREO FDF Operations Concept document. Work is also progressing on the Operations Interface Agreement with the Deep Space Network (DSN). Currently, STEREO's planned launch date is no earlier than April 11, 2006.

[Technical contacts: Michael Mesarch]

2.1.15 Time History of Events and Macroscale Interactions during Substorms (THEMIS)

Members of the FDAB participated in the Flight Dynamics and Missions Operations Program Review Panel for the THEMIS mission in October 2004. The THEMIS mission team, consisting of members from the University of California, Berkeley (UCB), Swales Aerospace, and GSFC presented their trajectory design, attitude determination and control, and mission operations concepts. Karen Richon, who led the Independent Flight Dynamics and Mission Operations (FD&MO) Review Team, coordinated the review for the THEMIS Program Office at GSFC. The FDAB review panel members consisted of Karen Richon, Susan Hoge, Richard Harman, and FDAB contractors Neil Ottenstein, Greg Dell, and Conrad Schiff of a.i. solutions, Inc. The primary purpose of the review was to determine if the THEMIS team was ready to proceed with the Operations Readiness Review (ORR) scheduled for November 2004. Based on the findings of the review panel, the ORR was postponed until February 2005 so that UCB and Swales could improve their operations procedures and complete their trajectory design. The FDAB provided consultation and analysis support during the rest of the year and assisted UCB in demonstrating at the ORR that the THEMIS team had made excellent progress and was well on their way to a successful October 2006 launch. Over the course of the year, the FDAB has monitored the progress of the THEMIS team in the FD&MO areas.

In addition to the independent review support, several FDAB engineers supported UCB in several flight dynamics areas. Kevin Berry developed the propulsion system model used in the maneuver planning software (Goddard's GMAN program) for UCB under the guidance of Bob DeFazio. Bob DeFazio also provided invaluable assistance in helping UCB develop maneuver support procedures. Mark Beckman provided consultation for orbit determination and prediction error analysis. Rick Harman provided an updated version of the Mission Spin-Stabilized Spacecraft (MSASS) software for THEMIS and assisted in the training of UCB personnel in the use of that tool. He also provided consultation support for attitude determination and calibration procedures. Dave Mangus provided support in the area of Attitude Control. The FDF is currently supporting UCB in the verification of their Berkley Ground System (BGS) antenna for the THEMIS mission.

[Technical contacts: Robert L. DeFazio and Karen Richon]

2.2 OPERATIONAL MISSIONS

2.2.1 EOS Support

http://eos-aura.gsfc.nasa.gov/

In November 2004, the FDAB took over responsibility for the non-routine Flight Dynamics support for the Earth Observing System (EOS) missions (Terra, Aqua, and Aura) that had previously been performed by the Flight Operations Team (FOT). This change was made to help focus the various activities required for those missions as they became part of the Earth Science Afternoon Constellation. It was felt that management under FDAB would help obtain the necessary resources for planning coordinated inclination maintenance maneuvers, monitor the on-orbit constellation missions through the Constellation Coordination System, perform any required constellation analysis, and provide routine software maintenance and system administration for the EOS Flight Dynamics System (FDS). The FOT retained control of the daily product generation, but FDAB performed Quality Assurance (QA) of their activities as well as performing all other nonautomated processes.

The nonroutine support involved providing several people who became part of the FOT. This year we have two additional people to back up the lead Flight Dynamics FOT engineer, who previously only had one partially-trained backup engineer. The team has pulled together official procedures and training documentation to ensure proper documentation of Flight Dynamics Engineer duties, as well as performed acceptance testing of new software builds, and performed various analyses for the EOS missions.

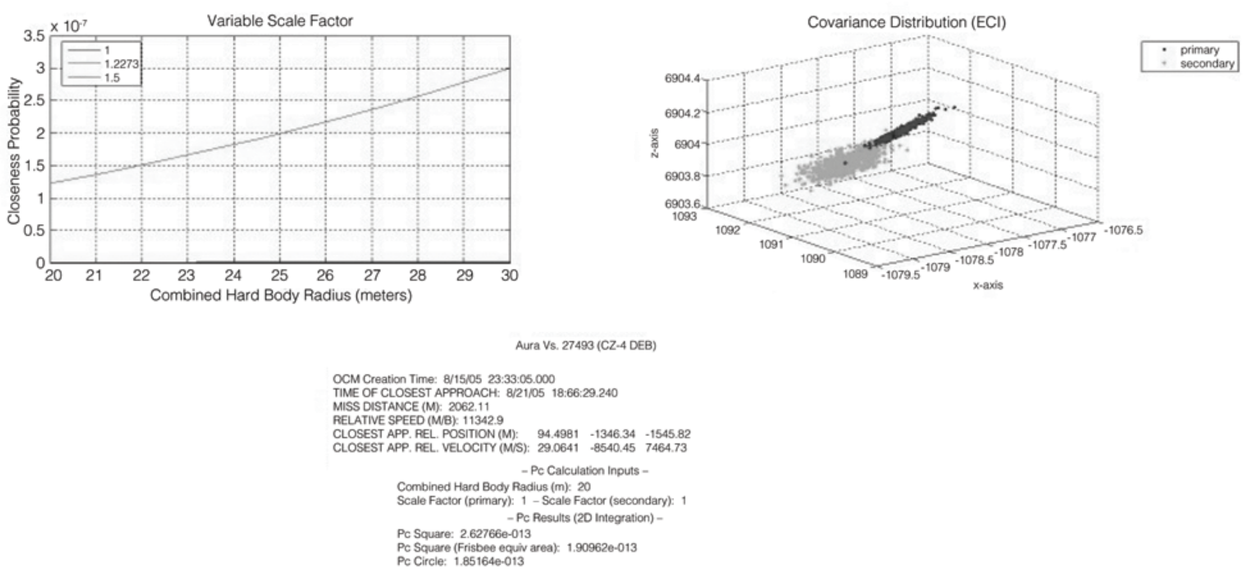

Figure 2-8. Sample Tool Suite Output for Conjunction Evaluation

A new activity performed under this task has been the creation of a conjunction assessment (CA) process for the EOS missions. Based on predictions supplied by the Cheyenne Mountain Operations Center (CMOC), task personnel evaluate the threat of collision between identified objects and various Earth Science Mission Operations Project assets. In order to perform these evaluations, the task developed a tool suite that can determine the closeness probability, detect the sensitivity of the conjunction to the orbit determination characteristics, and analyze the effect of various potential avoidance maneuvers on the asset orbit and science requirements. Figure 2-8 shows sample output from the tool suite that indicates the geometry of the conjunction plane and the closeness probability. In addition, the task created a database to

enable statistical evaluation of all the data obtained from the CMOC screenings. Weekly statistics are provided to management from the database, an example of which is shown in Figure 2-9. The task developed procedures and a draft operations concept document while establishing working relationships with Johnson Space Center (JSC) and CMOC personnel. The task performs maneuver sensitivity analysis for objects predicted to pass close to EOS spacecraft during a routinely scheduled maneuver. Next year, the task plan is to continue development of the tool suite as more experience is gained with the conjunction assessment problem. Specific issues that will be addressed include adding a probabilistic risk assessment component to the close approach effort for both the Morning and Afternoon Constellations.

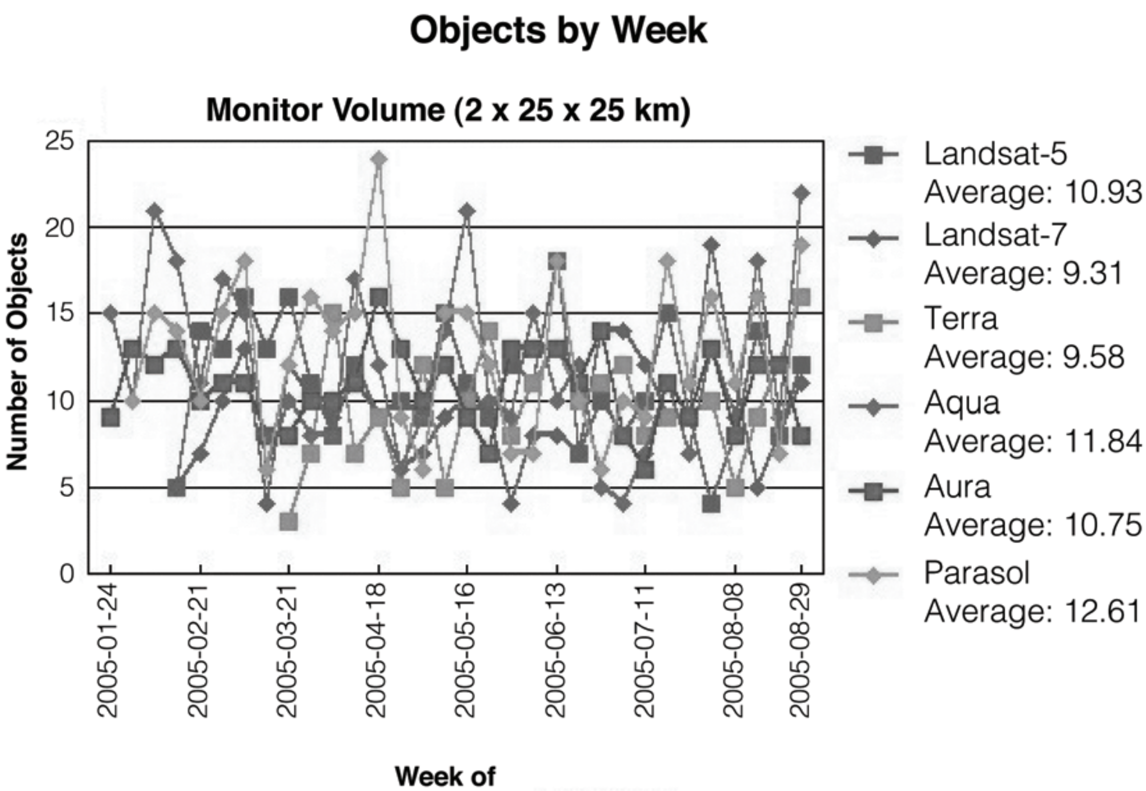

Figure 2-9. Weekly Violations of Monitor Volume for Various Spacecraft

[Technical contact: Lauri Newman]

2.2.2 Far Ultraviolet Spectroscopic Explorer (FUSE)

http://fuse.pha.jhu.edu/

FUSE gives astronomers the unique capability of observing the universe's far ultraviolet portion of the electromagnetic spectrum (approximately 90–120 nm). Studying this light, astronomers are able to better understand the conditions just after the Big Bang, as well as the chemical evolution of galaxies and interstellar gas clouds.

By the fall of 2001, the FUSE spacecraft had lost three reaction wheels and is currently controlling with only a skew wheel.

The FDAB developed a simple safe-hold design that will maintain a power positive attitude in the event that attitude determination and all of the gyros are lost. The new safe-hold algorithm is required to point the solar arrays at the Sun during the daylight portion of the orbit and hold the instrument out of the orbit plane without the use of gyros. The algorithm relies on a physical concept: If you apply “B-dot control” to a body that has an internal momentum, that momentum will tend to precess away from the orbit plane. “B-dot control” is simply the difference between consecutively measured magnetic fields. Holding a wheel, parallel to the instrument, at near constant speed (internal momentum), the wheel and instrument will precess away from the orbit plane. The wheel is then slightly modulated to maintain Sun pointing. This algorithm was extensively ground tested and uploaded onboard the spacecraft along with other Orbital Science Corporation (OSC) generated patches.

The Johns Hopkins University FOT is attempting momentum management by selecting targets that will either spin up or spin down the remaining wheel. The process is slow and can result in unfavorable conditions. The FDAB is investigating a new process, using Boids logic, which will take into account the spacecraft attitude, gravity gradient and gyroscopic torques, as well as wheel momentum to select the best targets for momentum management.

[Technical contact: Dave Mangus]

2.2.3 Hubble Space Telescope (HST) Two- New Pointing Control Systems

https://edocs1.hst.nasa.gov/

The year 2005 was a busy one for the HST Project. Aside from potential robotic servicing missions, and plans for a fourth Shuttle servicing mission, HST pursued development of 1) a science-mode, two-gyro control system; 2) a science-mode, one-gyro control system; and 3) a safe-mode, zero-gyro controller. All of these are intended to maximize the useful lifetime of the telescope in view of the uncertain servicing mission availability.

The two-gyro system (TGS) comprises a sequence of sub-mode controllers—progressing from magnetometers to star trackers to, finally, the Fine Guidance Sensors (FGS). Rate estimates for the missing third axis are derived from these attitude sensors. There is significant overhead in advancing the controller through the coarser modes into the final FGS control, however, once there, the on-orbit performance is as good as the 3-gyro system, showing an orbit-averaged 7 marcsec of jitter. Relying on the demonstrated success of this controller, the HST project, with approval by NASA HQ's Science Mission Directorate Program Management Council, in August 2005 shut off one of the remaining working gyros, gyro 4. This transistion to TGS control will (hopefully) extend mission life by reactivating gyro 4 at a future date upon loss of another gyro. Further enhancements, such as operating with a single FGS, and modifying the acquisition logic for increased robustness against guide star loss-of-lock, are under study.

The one-gyro system is also intended to support science. It is still in the development stage, however the algorithms have been incorporated into the high fidelity mission simulator, HSTSSTETIM. This controller is not likely to provide 7 marcsec of jitter, but is nonetheless expected to be useful in a degraded pointing system. Loss-of-lock of the very faint FGS stars (19^{th} magnitude) is expected to be a significant issue here.

The Zero-gyro Kalman Filter (ZGKF) sun-point controller is a safe mode intended to provide 6° of Sun pointing attitude error at low rates ($.03°s^{-1}$). Such control would be useful in supporting a robotic docking with HST. The existing zero-gyro safemode is a momentum biased system which, as shown in on-orbit

use, provides 50º attitude control, drifting somewhat during orbit night. It relies on a coarse sun sensor (CSS) sun vector during the day, supplemented by the magnetic field measurements from the Magnetometer system. The new ZGKF controller is an extended Kalman filter, which attempts to derive rates from the same sensor suite, without a momentum bias. It shows great potential and and has undergone several peer reviews, but requires more development and fine tuning before it is available for prime time.

FDAB personnel are working closely with Lockheed Martin and HST Project personnel to develop these algorithms.

[Technical contact: Michael Femiano]

2.2.4 Hubble Space Telescope (HST) Updated Orbit Decay Predictions

FDAB personnel have been working diligently to improve NASA's understanding of the HST's future by updating and improving our long-term prediction of the telescope's orbit. This effort is of particular interest as the Agency considers a fourth HST Servicing Mission by Shuttle (Servicing Mission 4, or SM4) to replace failing components, install new and improved science instruments, and possibly install a propulsive deorbit module (PDM) for the eventual controlled reentry and demise of the telescope. FDAB predictions of HST orbit decay provide critical insight into the urgency with which NASA must act to install a PDM.

This study once again brought selection of solar flux prediction methods to the forefront of our attention, generating interest in the subject at all levels of NASA. Long-term orbit decay prediction is highly sensitive to solar weather and in particular to extreme ultraviolet radiation from the Sun. Increased solar flux causes heating and expansion of Earth's upper atmosphere, resulting in higher atmospheric density at orbital altitudes, and increased orbit decay rates. Scientists have long been studying solar weather and the 11-year cycle of the Sun to improve long-term solar flux prediction (see Section 5.7 for information on Schatten's prediction method).

Based on historical HST decay rates and physics-based solar weather prediction methods, FDAB analysts currently predict an uncontrolled HST reentry no earlier than the year 2025 (assuming no further Servicing Missions and orbit reboosts). This estimate uses a hybrid solar flux prediction approach, with Schatten "plus two sigma" solar flux prediction for the upcoming solar cycle (cycle 24), and a more statistically conservative solar flux prediction for the following cycle (cycle 25). The HST Program Office led an effort to independently verify these FDAB results, gathering results from the Aerospace Corporation, Draper Labs, and NASA's Orbit Debris Program Office at the JSC. The independent analyses helped build a consensus on the predicted HST reentry date, and convince the HST Program Office that FDAB is on the leading edge of long-term orbit decay analysis.

[Technical contact: Bo Naasz]

2.2.5 LandSat-7

http://landsat7.usgs.gov/index.php

One of the three gyros on Landsat-7 showed indications that it may fail in the near future. On May 5, 2004, the United States Geological Survey (USGS) decided that the safest course of action was to turn off the failing gyro and switch to the redundant gyros to continue taking science data.

A major concern was that if another gyro failed, the spacecraft might not be able to lower its orbit out of the 700 km constellation. The spacecraft would take up valuable “real-estate” in the orbit and it may become a collision hazard for other spacecraft.

In FY04, the FDAB showed that a decrease of almost 20 km would be required to remove it completely from the 705 km altitude. A return to a 705 km altitude is unfeasible. FDAB propagated Landsat-7 orbit for one year, with and without drag. A comparison of the two propagated orbits showed that Landsat-7 should be safely out of range of the 705 km altitude location in about 5 months. If Landsat-7’s orbit were allowed to decay in this way, the orbit should be monitored for close approaches with other sun-synchronous spacecraft for the 5 month period. If close approaches were noted, the spacecraft approaching Landsat-7 would have to take evasive action.

The results of the FDAB FY04 study set up the process for FY05. The first phase was to develop methods for maintaining safe orbit and attitude maneuvers with only one, two-axis gyro. The FDAB assembled a brainstorming team to explore new ways of continuing the mission and decommission the spacecraft when needed. The team came up with about a dozen concepts. Cost and schedule reduced the concepts down to deriving rates using the Earth sensor, magnetometer, or the coarse Sun sensors. The new software module continually derives the rates from the selectable sensors and is monitored from the ground. A new, onboard, 10^{th} order magnetic field model, supplied by the FDAB, was also developed and uploaded to the spacecraft for derived rate use. This derived rate software module can be switched into any control mode on the spacecraft.

A very successful review was held on August 31, 2005. High-level Goddard system engineers and some of the original Landsat-7 engineers supported the review. After the inclination maneuver is completed in the Fall of 2006, the team will begin the second phase of tightening the pointing performance to obtain science data on a single gyro.

[Technical contact: Dave Mangus]

2.2.6 Rossi X-ray Timing Explorer (RXTE)

http://agile.gsfc.nasa.gov/docs/xte/xte_1st.html

Since 1995, the RXTE has been observing bursts of x-rays that come from high-energy phenomena including black holes, neutron stars, and x-ray pulsars. The RXTE performs multiple slew maneuvers, to point to the various ground selected targets. RXTE can dwell on a target with arc second pointing accuracy. This tight pointing can be accomplished using high precision gyros and star trackers.

During these slew maneuvers, there are times when the star tracker may not lock on the stars, or may lock on the wrong star. This results in the gyro estimated biases to be assumed larger than they actually are, therefore, RXTE could continue to slew to undesired targets. There are also times when the tracker/gyro system corrects the problem. The trick is to determine how long the Flight Operations Team (FOT) should wait before they intervene. Waiting too long could result in lost science data during a long recovery to normal operations time. The solution was to add an additional layer of monitoring. An FDAB RXTE ACS person is notified when any detection counter increments by one. This does not mean that a failure has occurred, but does monitor how close RXTE comes to a failure. The second part of the solution was to shorten the recovery time. The recovery procedure had many options that were streamlined as a near-term fix. For a long-term fix, the FDAB, in conjunction with the FOT and Chesapeake Aerospace, is developing a new flow chart to rewrite the recovery procedure.

[Technical contact: Dave Mangus]

2.2.7 Space Science Missions Attitude System Reengineering

The Space Science Mission Operations (SSMO) office utilizes many institutional services from the Flight Dynamics Analysis Branch (FDAB) Flight Dynamics Facility (FDF). Significant aspects of the support provided include attitude determination support, attitude sensor calibration support, orbit determination support, orbit maneuver support, and mission planning product generation. The desire of the SSMO management and the vision for FDAB is to transfer all routine attitude determination functions for legacy missions to their respective Mission Operations Center (MOC). This might be accomplished through either individual MOCs or via a consolidated MOC using a fleet support concept. Most recent and future missions do not require routine attitude support (e.g., a “definitive” attitude determination history) from FDF, because the onboard attitude determination meets the mission requirements. Some missions have implemented automated ADS functions in the MOC (e.g., Terra), when onboard attitude determination did not meet mission requirements. The FDAB FDF will remain a center of expertise for all orbit-related mission support functions and for attitude sensor calibration/anomaly investigation.

The first SSMO mission to attempt re-engineering of the institutional FDF ADS routine functions was Rossi X-Ray Telescope (RXTE). The MATLAB-based, Multi-mission Three-Axis Stabilized Spacecraft (MTASS) ADS system used in the FDF, required modifications to the telemetry processor, an upgrade of the operating system (Windows 2000 to Windows XP Pro), and an update to the MATLAB version. These changes were required for interface compatibility and to meet security requirements in the new operations environment. New PC hardware was also purchased for the RXTE MOC to support the new requirements and automation of the routine ADS functions was discussed, but not implemented because of SSMO budgetary constraints. RXTE was the prototype, proof-of-concept development effort that preceded other planned SSMO mission attitude system re-engineering.

The RXTE re-engineering effort received approval near the beginning of FY04 with some low-level activities accomplished using existing MOC equipment and the existing RXTE MTASS ADS. The MOC hardware and licenses arrived in early 2005 and software changes were implemented in MTASS to accommodate the new telemetry format in the MOC. Acceptance testing of the modifications was accomplished via a joint effort between FDF analysts and the RXTE FOT members. A series of benchmark tests were developed to ensure consistency of results between the FDF institutional ADS system and the modified version developed for the RXTE MOC. After verification of the benchmark tests was completed, parallel operations were conducted and the results compared well. An Operations Readiness Review (ORR) is planned in the near future and routine attitude operations will be transferred to the RXTE MOC following completion of the ORR.

Several other SSMO missions are targeted for attitude system re-engineering with the preliminary assessments already completed. These missions include Wind, Polar, Solar and Heliospheric Observatory (SOHO), and Advanced Composition Explorer (ACE) with the goal of 12/2006. A report was generated by FDAB analysts and presented to SSMO management documenting the required capabilities for each legacy mission and possible support approaches.

[Technical contact: David Tracewell]

2.2.8 Swift

http://swift.gsfc.nasa.gov/

The Swift gamma-ray observatory was successfully launched from Cape Canaveral on a Delta II launch vehicle on Saturday, November 20, 2004 (day 325) at 17:16:00.611 GMT with spacecraft separation

occurring at 18:36:05.2 GMT. The Swift spacecraft was launched into a 585×600 km 20º inclination Low Earth Orbit (LEO). The Western Range (WR) Radar sites and the Space Network's (SN) Tracking Data Relay Satellite (TDRS) System (TDRSS) supported Swift launch-day activities providing tracking data to the Flight Dynamics Facility (FDF) via real-time interfaces. FDF provided acquisition data in the form of IIRVs, IRVs and TLEs to the MOC, USN, WR, and SN in support of Swift Launch and Early Orbit (L&EO) activities. FDF provided special requests to the Swift MOC and supporting stations.

FDF received 46 character C-band tracking data in real-time from the WR sites. FDF used all six C-band skin-tracking supports to perform initial Swift orbit determination before the spacecraft was in coherent mode. FDF received both coherent and non-coherent SN tracking data from TDRS satellites in support of Swift launch day activities. Valid coherent TDRS range and Doppler tracking data was used for launch day Orbit Determination (OD); valid noncoherent TDRS Doppler tracking data was used for launch day local oscillator frequency (LOF) characterization and monitoring. The LOF offset noted on the primary flight transponder used for all launch day events started around -800 Hz and continuously drifted down to around -400 Hz by end of launch day, staying well within TDRS acquisition range. FDF used coherent TDRS tracking data to generate the delivered launch day OD ephemeris. The quality of the TDRS coherent tracking data was excellent.

The Swift launch day OD ephemeris compared very well to the nominal and actual spacecraft separation with consistent ephemeris compares of ~ 5km, translating into differences of less than 1 s being observed on launch day. FDF provided flight dynamics products to the Swift MOC, SN, Universal Space Network (USN), Malindi (via the MOC) and C-band radars via real-time interfaces and the FDF Product.

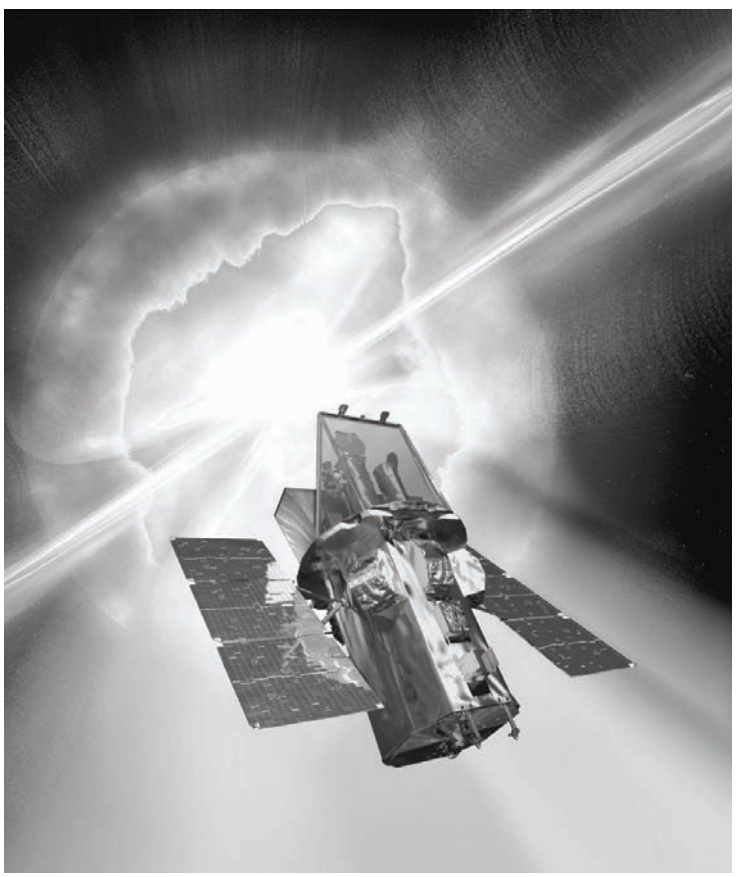

Figure 2-10. Swift Spacecraft

FDF provided Swift OD based ephemeris and acquisition data for L+7 days in accordance with the Memorandum of Understanding (MOU). FDF performed Swift L&EO OD using coherent TDRS tracking range and Doppler tracking data. On L+6 days, the Swift Project requested FDF extend OD based ephemeris support to L+14 days because of uncertainty with North American Defense Command (NORAD) Two Line Elements (TLEs), but requested FDF terminate Swift acquisition data support. On L+12 days, after several SN acquisition problems, the Swift MOC reported finding errors in the MOC IIRV acquisition data generation process and requested FDF resume generation and delivery of Swift acquisition data until L+14 days when extended OD supported expired. FDF provided the SN acquisition data with no problems being noted.

Using TDRS one-way non-coherent tracking data, FDF monitored and characterized the Swift primary flight transponder's local oscillator frequency (LOF) for L+7 days in accordance with the MOU and subsequently, during the L+14 day Swift FDF extension. Because of a quick LOF drift rate approaching the SN acquisition limits, FDF recommended the Swift Project update the Swift primary transponder center frequency to optimize Swift L&EO SN acquisition. Based on the FDF recommendation, the Swift MOC successfully updated the center frequency a couple times during L&EO using GCMR.

In summary, FDF Swift L&EO support was nominal.

[Technical contact: Mark Woodard]

2.2.9 Tropical Rainfall Measuring Mission (TRMM)

http://trmm.gsfc.nasa.gov/

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA), and is designed to monitor and study tropical rainfall. TRMM was launched in November 1997.

FDAB personnel continued development of a controlled re-entry plan for the TRMM spacecraft. In November 2004, the TRMM mission manager provided funding for a Johnson Space Center (JSC) Flight Design and Dynamics Division (FDDD) study to verify the validity of the debris footprint for the FDAB nominal re-entry maneuver plan. FDAB personnel contributed to the development of a statement of work for the study. The study results, delivered in December 2004, were in excellent agreement with the FDAB predictions. FDAB personnel supported a Guidance, Navigation, and Control delta peer review of the re-entry plan in mid-December 2004.

In early 2005, fuel utilization predictions indicated that the fuel remaining trigger level for controlled re-entry of 138 kg would be reached mid-to-late 2005. In June 2005, the NASA Administrator directed that negotiations be opened with JAXA to reach an agreement of liabilitym which would waive the requirement for a controlled re-entry and allow TRMM to continue operating until fuel depletion. Final negotiations were completed and the official directions to stand down were issued. There is no longer enough fuel onboard to complete a successful controlled re-entry, therefore, TRMM is scheduled to operate until the remainder of the fuel has been depleted.

[Technical contact: Frank Vaughn]

2.3 FLIGHT DYNAMICS FACILITY (FDF)

2.3.1 FDF Overview

http://fdf.gsfc.nasa.gov/

The FDF provides orbit determination, attitude determination, maneuver planning, acquisition data services, and launch vehicle services for Earth and lunar orbiting missions. The FDF supports approximately 20 missions on a regular basis. In FY05, the FDF supported new missions NOAA-N and Swift, as well as 15 expendable launch vehicles. The highlight of FDF support this year was the successful return to flight of the Space Shuttle. The FDF was an important part of the ground support for the STS mission. Because this was the first flight since the Columbia accident, there was much media attention surrounding this mission. The FDF hosted local media personnel in the facility to experience the launch and landing from the FDF standpoint. The FDF was featured on the front page of the *Baltimore Sun* newspaper for both the launch and landing.

Another highlight of FY05 was the continuing reengineering effort within the FDF. Several important pieces of infrastructure hardware were upgraded and the operating system upgrade continued as planned. Over the next year the FDF expects to complete both the hardware and software upgrades and enter into a process assessment phase in order to plan for future mission support.

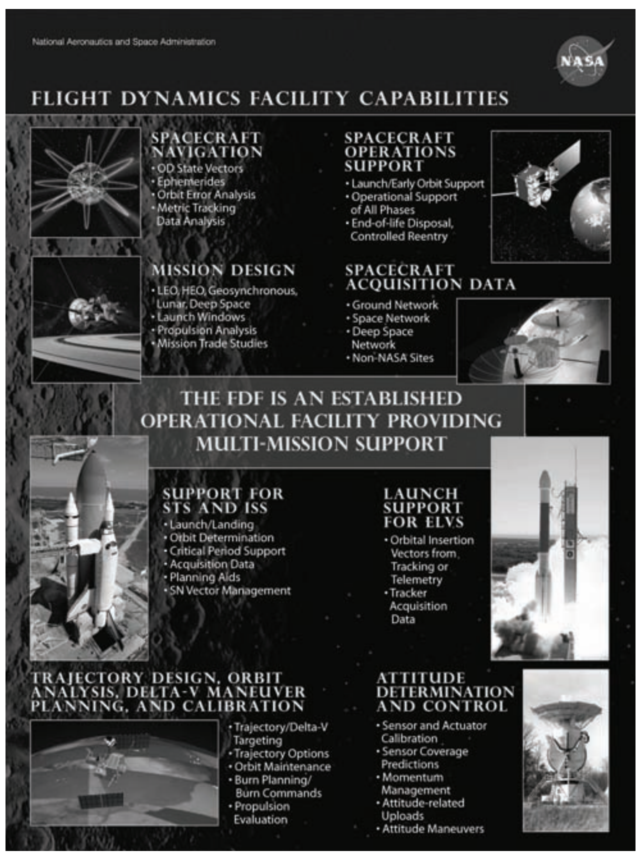

Figure 2-11. Flight Dynamics Facility Capabilities

[Technical contact: Sue Hoge]

2.3.2 Attitude Operations

The FDF Attitude Operations Task provided operational support for 11 GSFC missions. These included ACE, Earth Radiation Budget Experiment (ERBS), Polar, RXTE, SOHO, Submillimeter Wave Astronomy Satellite (SWAS), Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP), Transition Region and Coronal Explorer (TRACE), TRMM, Upper Atmosphere Research Satellite (UARS), and Wind. Support included attitude determination and health and safety monitoring, Attitude Product deliveries to the appropriate flight operations team (FOT), anomaly resolution, and special request support. Highlights for the year include:

- Analysis of UARS onboard attitude errors reported by the High Resolution Doppler Imager (HRDI) instrument team. The task traced the attitude errors to mistuned parameters in the onboard Kalman filter algorithm.
- Investigation of anomalous bright object detections by RXTE star tracker #1.
- Support of RXTE attitude reengineering to move attitude determination functions into the MOC.
- Support of decommissioning activities for UARS.
- Support of decommissioning activities for ERBS.

[Technical contact: Mark Woodard]

2.3.3 Expendable Launch Vehicle (ELV) Support

The FDAB Flight Dynamics Facility ELV Support Task has successfully supported 15 missions since the beginning of FY05. Mission support includes generation and transmission of premission acquisition data and planning products, and real-time acquisition updates based on processing of inertial guidance data and tracking data during flight. The missions supported in FY05 are listed below:

November 20, 2004—Delta II/Swift
December 17, 2004—Atlas V/ AMC-16
January 12, 2005—Delta/Deep Impact
February 3, 2005—Atlas III/AC-206 (MLV-15)
February 28, 2005—STARS/Global Flyer
March 1, 2005—SeaLaunch/SL-18 (XM-3)
March 11, 2005—Atlas/AV-004 (INMARSAT-4 F1)
April 15, 2005—Pegasus/DART
April 26, 2005—SeaLaunch/SL-15 (Spaceway-1)
May 20, 2005—Delta II/NOAA-N
June 23, 2005—SeaLaunch/SL-14 (Telstar/Intelsat Americas-8)
August 10, 2005—Atlas V-007/MRO
September, 26, 2005—P-3/COBRA DANE

[Technical contacts: Frank Vaughan and Michael Mesarch]

2.3.4 Human Spaceflight Support

2.3.4.1 STS Support-114 Return-to-Flight

During FY05, the FDF supported the numerous Space Transportation System-114 (STS-114) Discovery Return-to-Flight (RTF) efforts. Included in the RTF efforts were full-up simulations that included both the Ground Network (GN) and the Space Network (SN). These simulations exercised FDF premission and launch support procedures, including ascent abort cases. FDF personnel also developed and ran internal and FDF/Space Network-only proficiency simulations. These simulations were designed to train

new FDF Shuttle support personnel, as well as to strenuously exercise FDF and SN contingency procedures, which were not typically exercised during the full Network simulations. To ensure new FDF Shuttle support personnel were properly trained and that the training was documented, FDF personnel developed and wrote an STS support personnel certification plan. FDF personnel also participated in an intercenter Six-Sigma Return-to-Flight Action Team whose objective was to identify and mitigate all significant RTF risks. FDF personnel supported Network RTF meetings and teleconferences and reviewed STS program documentation and provided input as needed. FDF personnel also supported the Network Support Group (NSG) meetings at NASA Johnson Space Center (JSC) in Houston, Texas in March and September 2005 and Operations Readiness Reviews in January and May 2005. Finally, the FDF successfully supported the STS-114 Logistics Flight 1 (LF1) mission from July 26 through August 8, 2005. The FDF provided support in the technical areas of acquisition data generation for the GN and SN for all mission phases, metric tracking data evaluation, backup orbit determination support for Emergency Mission Control Center (EMCC) activation if required, and planning product generation for Network scheduling purposes. During the mission, the FDF provided the new EMCC displays to the JSC EMCC personnel via the Internet for their review and comments.

Figure 2-12. FDF During STS-114 Operations

2.3.4.2 *ISS Support*

During FY05, the FDF supported two Soyuz crew rotation missions to the International Space Station (ISS): Soyuz 9S in October 2004 and Soyuz 10S in April 2005. The FDF also began preparations for supporting the Soyuz 11S mission, scheduled for early FY06. FDF personnel also supported several ISS reboosts during the year. At the request of the JSC ISS Trajectory Operations Officer (TOPO), FDF personnel presented an overview of the FDF ISS orbit determination process to the ISS TOPO group during an NSG trip to JSC. The FDF continued to evaluate ISS tracking data and provided the networks with weekly local oscillator frequency (LOF) reports. FDF personnel also participated in meetings and

teleconferences to discuss support of, and reviewed and commented on documentation for, the European Space Agency's Autonomous Transfer Vehicle (ATV) and Japan's H-II Transfer Vehicle (HTV).

[Technical contacts: John Lynch and Chad Mendelsohn]

2.3.5 Maneuver Operations

The FDF Maneuver Support Task monitored and planned orbit maneuver operations for several NASA spacecraft, including Wind, SOHO, ACE, and Polar. These orbit maneuver operations consisted mainly of station keeping or orbit maintenance maneuvers. Since January 2005, the task has performed the analysis and planning of three maneuvers for Wind, three for SOHO, and two for ACE. In April 2005, task personnel provided support for a Polar attitude adjustment maneuver, showing that the maneuver would have the desired negligible effect on the orbit. Task personnel also participated in end-of-life operations for ERBS and UARS, planning orbit maneuvers to ensure requirements for disposal and reentry were satisfied. At the time of this writing, both spacecraft contained large amounts of propellant to be depleted through several burns of long duration in the September–October 2005 timeframe. For the ERBS spacecraft the burns serve only to empty the propellant tanks, leaving the orbit unchanged; for the UARS spacecraft, the orbit perigee will be lowered while burning all remaining fuel onboard.

[Technical contacts: Linda Kay-Bunnell, Robert DeFazio and Dave Quinn]

2.3.6 Metric Tracking Data Evaluation (MTDE)

The GSFC Flight Dynamics Facility’s MTDE Task is staffed by Honeywell Technical Services. The task provides tracking network validation and calibration, STS support, ELV support, space mission support, and new tracking antenna certification support for missions supported by, and tracking systems used by, the GSFC FDF. The task successfully prepared for support of the STS-114 return-to-flight mission, confirming the tracking network was meeting the STS support requirements, and successfully supported the STS-114 mission in July and August of 2005. The task performed antenna certification for several different antennas, including the USN sites, the 11m antennas in Svalbard and Alaska, and the DataLynx 11m antenna.

[Technical contacts: Greg Mar and Sue Hoge]

2.3.7 Orbit Operations

This year has been extremely active for the FDF Orbit Operations group at GSFC, supporting 40+ missions which range from suborbital balloon missions to libration point missions and LEOs, High Earth Orbit (HEOS) and Geosynchronous Earth Orbit (GEOs) in between. They have provided orbit determination and acquisition data to many flight projects, as well as several hundred separate products each month.

The group successfully supported the Swift satellite launch and provided orbit determination support until the onboard orbit determination system was initiated and checked out. The Gravity Probe-B orbit support, originally planned to be a few days, was finally completed in October 2005.

The group supported the STS Return to Flight by providing orbit determination and acquisition data for the Shuttle. They also have been kept busy supporting the decommissioning operations of the UARS and ERBS satellites. These satellites are depleting their fuel before decommissioning in order to be less of a

risk to other orbiting satellites. UARS maneuver operations are decreasing the orbit altitude so that the satellite will reenter within the 25 year requirement. ERBS is performing its depletion maneuvers so that the orbit altitude does not decrease. This was done to prevent ERBS from deorbiting to the International Space Station orbit in the near future. The FDF Orbit operations team has supported every maneuver, providing orbit determination and acquisition data for each maneuver.

[Technical contact: Karen Richon]

2.3.8 Software Maintenance

This task is responsible for the development and maintenance of the Flight Dynamics software in support of the FDF institutional space mission operations activities and maintenance of the FDAB R&D software tools, to ensure consistency with the broader aerospace community practices. The flight dynamics software supports the following activities: attitude error analysis, prediction and determination; navigation, orbit prediction and determination, and error analysis; mission analysis, trajectory design and analysis, maneuver planning and acquisition data generation, and other mission planning tools.

This past year has been very productive for the software maintenance team. The main focus has been preparing for the Hewlett-Packard Unix (HPUX) 10.20 to HPUX 11.11 operating systems (OS) upgrade. The Software Team has management oversight responsibility for the entire OS upgrade. Throughout the year, the team has been recompiling, linking, and testing over 80 software Configuration Items (CIs), in preparation for upgrade efforts to begin in early October 2005. The team has also been working with the Sustaining Engineering team to plan the OS upgrade for over 30 servers and workstations. Lastly, the Software Team has formed a working group to assist Operations personnel in the inventorying, modification, and testing of all operational scripts for the new OS. These upgrades impact everyone in the daily operations at the FDF, so the timelines have been carefully planned.

Another major initiative started this year has been the migration of Attitude Operations, out of the FDF and into the MOCs. For the first mission, RXTE, the software team ported the existing HPUX 10.20 attitude determination system (running under Matlab 4.8 in the FDF), to a new Windows XP platform, using Matlab 7.0, in the RXTE MOC. Phase I consisted of porting basic functionality required to perform routine attitude operations. Phase II, which is in the planning stage, will port additional utilities and other software required for performing calibration, trending, and anomaly resolution in the MOC. Phase I is currently undergoing acceptance testing by the RXTE MOC personnel. When completed in the early October 2005 timeframe, the system will be transitioned to an operational status in the MOC, and no longer supported in the FDF.

Another project highlight for 2005 was the Shuttle "Return to Flight" mission in July 2005. This was the first Shuttle flight since the Columbia tragedy in 2003. It was also the first Shuttle launch support provided by the FDF software team, since the transition of the Consolidated Space Operations Contract (CSOC) to the Mission Operations and Mission Services (MOMS) contract.

The software team is composed of experienced professionals who have gained a great deal of experience since their indoctrination in January 2004. The CM processes implemented in 2004 continue to be fully supported and practiced throughout the facility, and there is a better comprehension of software "best practices" in testing and delivering software. Overall, there is a higher level of expertise and we continue to take a proactive approach in identifying and resolving issues.

[Technical contact: Felipe Flores-Amaya]

2.3.9 Sustaining Engineering

During the past year, several FDF systems were upgraded. The prime Windows server was upgraded and reconfigured, a new tape backup system was made operational, and new network routers were installed. These upgrades were planned as part of the FDF reengineering process that began in 2004. In addition to the upgrades, the FDF administration systems were placed within the GSFC Center Network Environment (CNE) and the operational network was reconfigured for both closed and open network connections. A security risk assessment was conducted during this fiscal year and disaster recovery planning was begun.

The coming year will see the final phase of the FDF reengineering. This phase involves the installation of several new general computational servers, new database servers, and the final network reconfiguration of the FDF operation environment.

[Technical contact: Sue Hoge]

2.3.10 Disaster Recovery (Emergency FDF Operations Center Plan)

The Emergency FDF Operation Center plan is currently in development, and will outline possible threats, two distinct contingency situations based on those threats, and procedures for ongoing operations under the applicable contingency scenario.

The requirements were defined considering two distinct scenarios:

- A short term (up to 1 week) Center closure
- A long term (up to six months) Building 28 closure

The first scenario was considered in the event of a national emergency impacting the Washington, D.C. area or a natural disaster that forces the Center to close. The second scenario was considered in the event of a facility issue such as a fire or water damage.

In the development of the plan, it was determined that no new user requirements will be considered or accepted during the period that the FDF is under backup facility operations, and any required budgetary plus up for plan implementation and execution shall be assumed to be available from some NASA or Federal Government source.

A Threat identification and analysis table shows the likely emergency situations that may impact the facility and evaluates the overall risks associated with these potential events. The table shall be reviewed annually and updated as required. The table gives the following information based on the findings of the analysis:

a. Likelihood—the probability of a specific hazard event occurring.
   - Negligible: Improbable or cannot occur
   - Low: Can occur, but no known history
   - Medium: Has happened in the past
   - High: Happens annually or more often

b. Potential Loss—the impact on the facility, Center, or Agency if a hazard event occurs:
   - Insignificant: Minor interruption of work
   - Limited: Loss of workdays or temporary loss of building
   - Significant: Fatality or loss of building

- Catastrophic: Loss of capability to perform Center or Agency mission

c. Threat Ranking—the relative importance of the listed threats, based upon their likelihood and potential loss. Threat ranking uses the following matrix:

Likelihood	Potential Loss			
	Insignificant	Limited	Significant	Catastrophic
Negligible	0	0	0	0
Low	1	2	3	4
Medium	2	4	6	8
High	3	6	9	12

The Plan is specifically dedicated to defining contingency procedures for each scenario, including activation of a backup facility in Building 13, GSFC, and detailed network diagrams outlining the emergency operations center (EOC). Completion of this plan is anticipated by the end of the calendar year.

[Technical contact: Mika Robertson]

3.0 STUDY MISSION SUPPORT

3.1 INTEGRATED MISSION DESIGN CENTER (IMDC)

http://imdc.gsfc.nasa.gov/

The IMDC is a human and technology resource dedicated to innovation in the development of advanced space mission design concepts to increase scientific value for NASA and its customers. The IMDC provides specific engineering analysis and services for mission design and provides end-to-end mission design products.

The FDAB provides engineering expertise in the areas of trajectory design and attitude control. The trajectory engineers from the FDAB provide critical mission specific analysis and design for mission trajectories. Attitude control engineers provide expertise in the refinement of ACS requirements, sensor selection, actuator sizing, component placement and specification, control modes design, and risk assessment. Because of the nature of the innovative missions proposed by the customers, innovative solutions are envisioned in order to meet the science requirements. ACS engineers also identify tall-poles that require a revision of science requirements. Many of the tall-poles are related to formation sensing, tight attitude requirements, and fuel constraints. ACS engineers also provide critical cost analyses and trade studies to determine the lowest cost configuration that will meet the science requirements.

A total of 23 mission studies covering a wide range of mission types were supported. Some missions required point solutions while others required new technology concepts to achieve the science goals. The missions included low and high Earth orbits (including sun synchronous and Molniya orbits); Sun–Earth libration points L1 & L2; solar drift-away orbits; and missions to the Moon, Mars, and Venus. Studies included both single spacecraft designs and formation flying/constellation designs. Many of the formation studies required innovative ways of solving the problems posed by the customers.

Additionally, IMDC engineers supported the recent NASA Exploration Design Team activities, which combined Goddard's IMDC expertise with design groups from JPL, JSC, MSFC, LaRC, Glenn Research Center (GRC), Ames Research Center (ARC), and the Aerospace Corporation to create a multicenter, virtual design team. A design activity in August 2005 used the Mars Sample Return scenario to test out protocols in communications and data sharing.

[Technical contacts: Frank Vaughn, Michael Mesarch, and Joseph Garrick]

3.2 3D CLOUD-AEROSOL INTERACTION MISSION (CLAIM-3D)

CLAIM-3D is a mission proposal with a scientific goal to better characterize cloud vertical development and simultaneous aerosol microphysical properties. The scope of the mission covers the most important issues in climate forcing and water cycle today: climate change; fresh water availability; intensification of thunderstorms; and stratospheric transport.

FDAB personnel have continued supporting the development of the proposal since the IMDC study that took place in December 2004. Although the requirement to fly in formation with the Global Precipitation Measurement (GPM) spacecraft (400 km, circular orbit) poses no significant challenge because science data must be taken with Sun backlighting and sensor motion is limited to one axis of rotation, various attitude modes will need to be employed to achieve the science objectives. Taking into consideration the sun angle (both the beta angle and with regard to the space craft body axes), a spacecraft roll constraint,

instrument pointing modes, and movement of targets due to the rotation of the Earth, implementing attitude control algorithms for the various instrument scanning modes can offer a challenge.

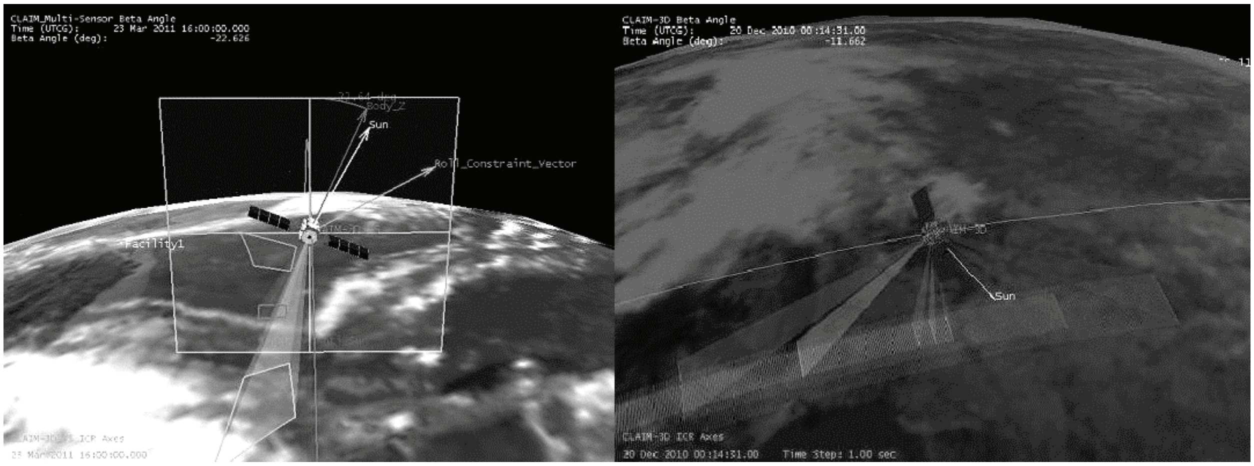

Figure 3-1. The CLAIM-3D Mission

A number of animations were developed by FDAB personnel to help the proposal team scientists and engineers visualize the spacecraft motion relative to intended targets and the Sun angle. The left side of Figure 3-1 illustrates the CLAIM-3D spacecraft pitching to maintain Sun backlighting, while the right side shows that spacecraft yaw is necessary to compensate for Earth rotation in order to scan the exact same target area after rotating the science instrument from a forward-pointing to an aft-pointing position.

[Technical contact: Chad Mendelsohn]

3.3 CONSTELLATION X: FORMATION FLYING MISSION

https://conxproj.gsfc.nasa.gov

The Constellation X project is conducting a study phase for a possible two spacecraft formation flying scenario. The two spacecraft consist of an x-ray mirror spacecraft and a detector spacecraft, flying in a precise formation 50 m apart in order to form a virtual x-ray telescope. The formation will be in a Lissajous orbit about the Earth–Moon/Sun L2 libration point. The FDAB is contributing to the study effort in two ways. The first is to participate in the generation of an error budget tool, designed to provide the tolerances for both estimation and control of the formation. The error budget, driven mostly by tight constraints on a reflection grating spectrometer, is likely to produce requirements on the order of millimeters for relative position control, and micrometers for relative position knowledge. The error budget tool, developed in Matlab by A.I. Solutions, Inc. will allow the scientists and project engineers to understand the error budget factors and conduct trade studies on the various components of the mission.

The FDAB is also developing a comprehensive simulation of the formation control and estimation during science observations and for retargeting of the formation. The simulation includes modeling of the orbit perturbations, such as differential gravity, solar pressure, and self-gravity, thruster modeling, simulated visible beacons, and corresponding sensors, with the ability to add various levels of perturbations and noise. The simulation currently includes a passivity based, nonlinear adaptive relative position control algorithm and a sliding mode observer to provide estimates of the relative position. Figure 3-2 shows preliminary results on the closed loop estimation errors from the simulation. The simulation development will continue with further enhancements of the sensor and actuator modeling, relative attitude estimation,

and control components, as well as planning and conducting the reorientation of the formation to a new science target.

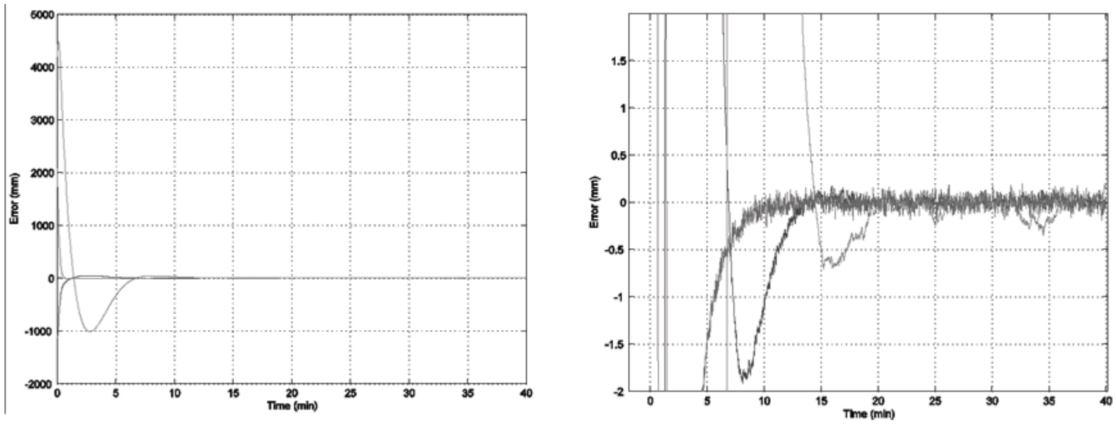

Figure 3-2. Preliminary Closed Loop Relative Position Estimation Errors for Constellation X

[Technical contact: Julie Thienel]

3.4 CONSTELLATION-X: EXTENDED OPTICAL BENCH

Constellation-X (Con-X) is a powerful x-ray observatory that will investigate black holes, Einstein's Theory of General Relativity, galaxy formation, the evolution of the Universe on the largest scales, the recycling of matter and energy, and the nature of dark matter and dark energy. Two concepts are being considered for the observatory. The first is a set of x-ray satellites orbiting in close proximity to each other and working in unison to generate the observing power of one giant telescope. The second concept involves one large telescope in a single spacecraft. The optical elements are packed within an extendible bus prior to launch. Once at the target orbit around the Sun–Earth L2 libration point, the bus is extended to its full-length capacity to bring the telescope into its nominal configuration. Both a 25 m as well as a 50 m long optical bench concept have been considered. The FDAB personnel provided a detailed feasibility study on the Con-X extended optical bench (EOB) concepts. These contributions are described in the following.

Attitude control system architecture along with candidate GN&C hardware were identified. Preliminary attitude control system design for the flexible EOB concepts were completed. A detailed model of the EOB was developed to assess the performance of the various pointing metrics of the system. This model included rigid spacecraft dynamics along with the flexible dynamics of the spacecraft bus (modes with frequencies of up to 50 Hz). Realistic models of the attitude sensors were included and used in an attitude determination system to provide refined estimates of spacecraft pointing error, as well as gyro bias errors. The primary nonsecular disturbance source acting on the spacecraft is expected to be the reaction wheel static imbalance forces and dynamic imbalance torques. A detailed model of the wheel dynamics, with multiple harmonics representations for the imbalance forces and torques, were included. A wheel speed controller was designed and incorporated for precise management of the wheel momentum. A linear model of the system was also developed for fast analysis of wheel disturbance effects.

Both the linear and the detailed EOB models were used to assess the pointing performance of the system. The impact of the wheel imbalance disturbances were characterized by sweeping the wheel speeds in the

range of operations, and then observing the pointing jitter induced at various frequencies. Closed-loop transfer functions were used to provide a worst-case scenario, with respect to phasing and harmonics, assessment of the pointing response of the system (see figure). This process was repeated for each of the four possible wheel orientations. The results of the linear analysis were confirmed using the detailed EOB model. Here, the critical wheel speeds, identified in the linear analysis, were used as the nominal speeds for each of the wheels. Time-domain analyses were used to verify the optimality of the predicted disturbances. The results indicated that the extended optical bench does meet its pointing stability and jitter requirements, at least at this preliminary juncture without having to resort to the use of any isolation system.

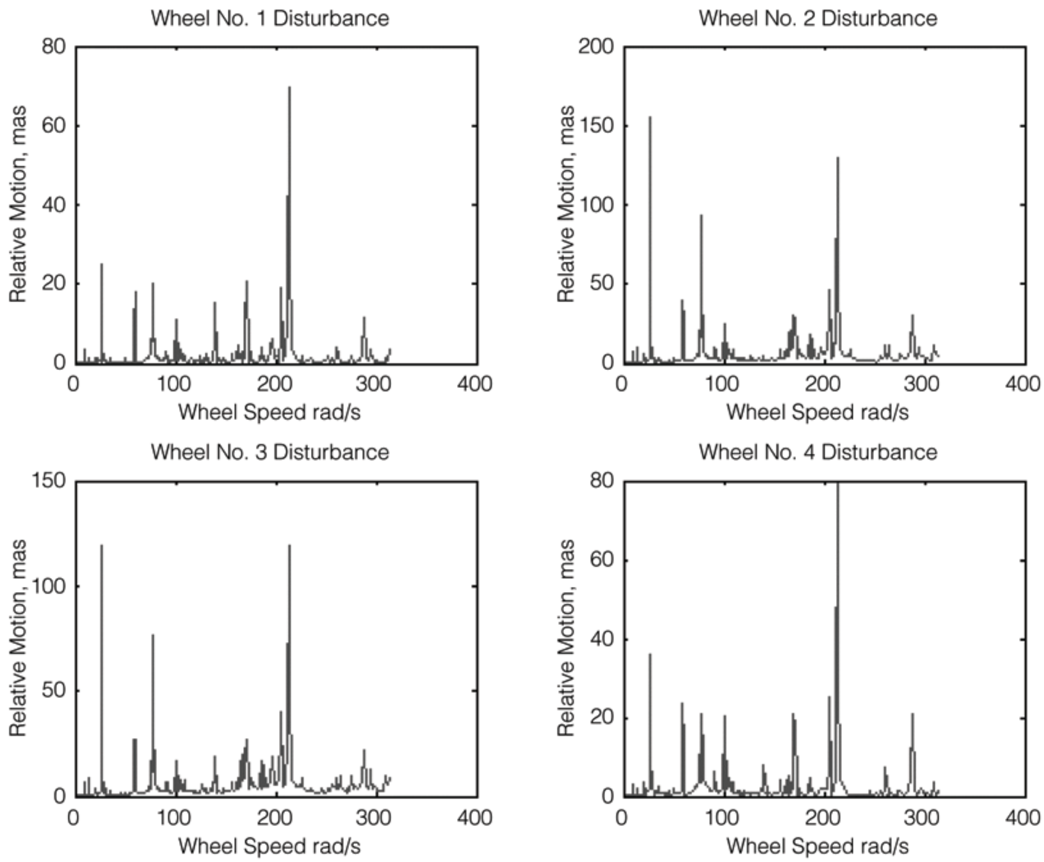

Figure 3-3. Pointing Performance of the EOB vs. Wheel Speed, Pitch Axis

[Technical contact: Peiman G. Maghami)

3.5 EXTRASOLAR PLANET IMAGER CORONAGRAPH (EPIC)

EPIC is a heliocentric mission designed to detect giant planets in other solar systems using its unique nulling coronagraph. The FDAB supported GSFC PI, Dr. Mark Clampin, again this year in the development of an upcoming EPIC Discovery proposal. Previously, the FDAB had performed trade studies to determine the optimum mission orbit. Because of science viewing requirements, a Sun–Earth L2 libration point halo orbit and an Earth-trailing heliocentric so-called “drift-away” orbit were the primary mission orbits considered. With regard to the choice of a mission orbit, it is important to note that EPIC must fire its thrusters approximately every four days in order to “dump momentum” from the reaction wheels. The FDAB had noted that if a Sun–Earth L2 orbit was chosen, these frequent momentum

dumps may adversely effect the orbit determination process, which is of great concern in this inherently unstable orbit. Based partly on this information, a heliocentric drift-away orbit was again chosen for EPIC. This year, the FDAB also recommended that one of Goddard's new "Golden Rules," which states that critical events should, where feasible, have real-time telemetry and command coverage, be considered. The Project accepted this recommendation and added an S-band transceiver to the proposal so that TDRSS support would be available for critical launch and early orbit operations. In addition to the aforementioned analysis, the FDAB also refined previous analyses of launch vehicle requirements, orbit determination requirements, nominal trajectory data, and nominal ground coverage statistics.

[Technical contacts: Steven Cooley and Greg Marr]

3.6 LASER INTERFEROMETER SPACE ANTENNA (LISA)

http://lisa.jpl.nasa.gov/

The primary objective of LISA mission is to detect and measure gravitational waves from massive black holes and galactic binaries in the frequency range of 10^{-4} and 0.1 Hz. The LISA mission comprises three identical spacecraft 500,000 km apart, which form an equilateral triangle (Figure 3-4). The center of the spacecraft formation is in the ecliptic plane, 1 AU from the Sun and 20° behind the Earth. LISA can essentially be viewed as a Michelson interferometer in space, with a third arm to provide wave polarization information, as well as redundancy. Each spacecraft contains two optical assemblies, with each assembly pointing towards an identical assembly on each of the other two spacecraft (Figure 1). A 1 W infrared laser beam (1 μm wavelength) is transmitted to the remote spacecraft via a telescope. The incoming beam is focused on a sensitive photodetector where it is superimposed with a fraction of the original local light. Each optical assembly includes an enclosure containing a free-flying proof mass, which serves as an optical reference mirror for the light beams. A passing gravitational wave changes the length of the optical path between the proof masses in one arm relative to the other arm. The spacecraft is used to provide a drag-free environment for each of the proof masses within it, by shielding the masses from solar radiation pressure. In order to be able to detect strain gravitational strain levels to the order of 10^{-23}, tight pointing and positioning requirements are placed on the spacecraft and the proof masses (e.g., acceleration requirement on each proof mass: 3×10^{-15} m/s^2/Hz$^{-1/2}$). To achieve these requirements, the LISA spacecraft are baselined to use electric propulsion thrusters and quadrant photodiodes for position and attitude control of each spacecraft, and capacitive sensing and actuation for relative positioning of each proof mass to the spacecraft.

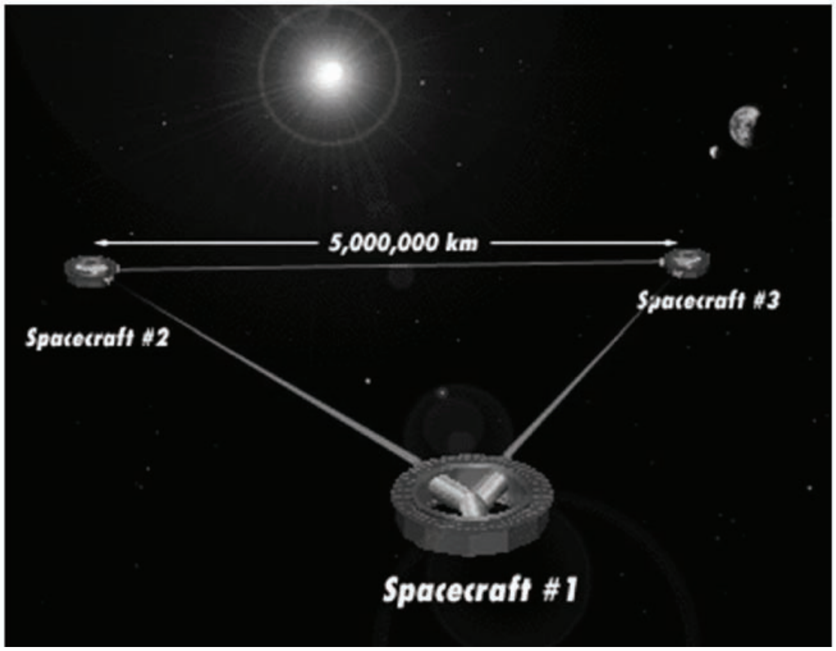

Figure 3-4. LISA Mission Concept

The FDAB personnel supported the LISA mission in a number of areas: (a) orbital design, analysis, and optimization; (b) dynamics and control modeling and analysis; (c) design and analysis of Disturbance Reduction System (DRS) control; (d) control system design and analysis of thrust stand facility. Each of these contributions is described below.

The nominal LISA formation consists of three spacecraft in heliocentric orbits trailing the Earth by about 20º, with inclinations near 1º with respect to the ecliptic plane. The mission design goals for LISA are challenging. The primary goal is to provide a formation that maintains a nearly equilateral triangle with sides near 5 million kilometers for the entire life of the mission, which is currently about 8 years. This has to be achieved entirely through careful orbit design, as continuous feedback control of the orbits is not permitted because it will interfere with the science measurements. We also must ensure that the sides of the triangle remain within 1% of 5 million kilometers and that the side rates never exceed 15 m/s. There is a secondary and competing goal that we keep the formation as close to Earth as possible for power reasons. Over the last year, we developed a new approach to optimal orbit design for LISA that takes into account these requirements. The approach begins by assuming a cost function that is explicitly dependent upon the relative geometries of the spacecraft, as well as the spacecraft's inertial states. The cost function is the average distance of the formation from Earth. The side length and side rate requirements are treated as constraints. We derived semi-analytic gradients of the cost and constraint functions with respect to the initial Cartesian states of the three spacecraft. This permits a Sequential Quadratic Programming (SQP) algorithm to efficiently solve the nonlinear programming problem. We found optimal trajectories for many LISA scenarios and mission lifetimes. The final results are a family of optimal trajectories, and an improved understanding of how the distance of the constellation from Earth affects mission life.

A number of simulation and analysis models of a single LISA spacecraft were developed and used to assess the feasibility of various technologies, such as Micro-Newton thrusters, inertial sensors, capacitive actuation, as well as the Drag-Free Control concept. These models, which have varying degrees of complexities, have been used for trade studies, control design and analysis, etc. The most complete of these is the 18-Degree of Freedom (DOF) LISA model, which includes full nonlinear translational and rotational dynamics of the spacecraft and each of the proof masses. Gravitational forces from the Sun, the

Earth, the Moon, and other significant planets are included. DRS control has been fully incorporated, along with instrument models of varying complexity. Approximations for self-gravity and nonlinear stiffness effects (from capacitive sensing and actuation) are included as well.

	0.1 mHz		1 mHz		10 mHz		0.1 mHz	
	Perf	Req.	Perf	Req.	Perf	Req.	Perf	Req.
Tel. Pointing (nrad)	2.89	8	2.78	8	3.67	8	5.82	8
PM1 Position, Sensitive (nm)	1.13	2.5	1.01	2.5	1.28	2.5	2.15	2.5
PM1 Position, Trans. (nm)	5.94	10	3.09	10	2.53	10	4.09	10
PM2 Position, Sensitive (nm)	1.13	2.5	1.02	2.5	1.29	2.5	2.19	2.5
PM2 Position, Trans (nm)	5.91	10	3.1	10	2.54	10	4.08	10
PM1 attitude (nrad)	149.7	200	97.1	200	4.6	200	5.8	200
PM2 attitude (nrad)	149.6	200	97.2	200	4.6	200	5.8	200
PM1 residual acceleration, Suspension X-talk (fm/s)	0.338	1.00	0.718	1.02	0.900	2.24	0.136	20
PM2 residual acceleration, Suspension X-talk (fm/s)	0.337	1.00	0.721	1.02	0.902	2.24	0.136	20
PM2 residual acceleration, Stiffness (fm/s)	0.535	0.7	0.441	0.71	0.517	1.56	0.865	14.02
PM2 residual acceleration, Stiffness (fm/s)	0.535	0.7	0.442	0.71	0.518	1.56	0.881	14.02

Table 3-1. LISA Disturbance Reduction System Performance

DRS control is a critical part of the LISA mission. It includes the overall control system architecture for the positioning and pointing of the spacecraft as well as the proof masses relative to the spacecraft. In the baseline configuration, the spacecraft, is responsible for maintaining a total drag-free environment (or as close as possible to it) for each of the proof masses. At the same time, fine pointing of each spacecraft with respect to the other two has to be maintained continuously. Preliminary design work for DRS control to achieve the desired pointing and positioning accuracy has been completed. This design is based on a decentralized approach to DRS control, wherein the spacecraft position control is designed to center about the proof masses, and the proof mass control maintains relative position and attitude with respect to the spacecraft. Two options were considered for proof mass translational control in the measurement axis, one with no control and the other with a very low-bandwidth controller.

As part the technology validation effort for LISA and other missions, a thrust stand facility is being developed at Goddard for characterization of the dynamics and noise characteristics of micro-Newton thrusters. The stand is based on a torsional pendulum concept, where a thruster is placed at an offset from the torsion fiber. A thrust force produces a torque about the fiber, and causes it to twist. In an open-loop mode, the twist angle measurement is used to compute the thruster force output. In a so-called “null” mode, capacitive sensing and actuation is used to regulate the twist angle, and the net actuation force/torque is used as a measure of the thruster force output. A digital controller was designed for actuating the capacitors in the null mode as well as regulating the power supply. A detailed simulation and analysis model for the thrust stand was developed to analyze the controller performance.

[Technical contacts: Peiman Maghami and Steve Hughes]

3.7 LIVING WITH A STAR, INNER HELIOSPHERIC SENTINELS (IHS)

The Inner Heliospheric Sentinels (IHS) *Sentinels* mission concept proposed by the GSFC Laboratory for Extraterrestrial Physics requires multipoint in situ observations of Solar Energetic Particles (SEPs) in the

inner-most heliosphere. This objective can be achieved by four identical spacecraft launched using a single launch vehicle into slightly different near-ecliptic heliocentric orbits. The spacecraft will utilize multiple Venus flybys to achieve different heliocentric orbits with perihelion at approximately 0.25 AU and aphelion at approximately 0.74 AU. The FDAB has performed trajectory design and analysis in support of this concept. Launch opportunities in 2012, 2014, 2015, and 2017 were identified. Baseline trajectories were generated, and ephemeris data and other orbit products were provided to the science team and the spacecraft team. Fuel mass requirements and navigation requirements were established. The spacecraft release strategy was analyzed and refined.

[Technical contacts: Dave Folta, Greg Marr, John Downing, and Linda Kay-Bunnell]

3.8 MOLNIYA IMAGER

The Molniya Imager mission concept proposed by GSFC utilizes spacecraft in highly eccentric Molniya orbits to perform climate studies. The FDAB has performed trajectory design and analysis in support of this concept. Extensive analysis has been performed to determine the science data return for various orbits including the nominal Molniya orbits.

[Technical contacts: Greg Marr, and Chad Mendelson]

3.9 SPACE TECHNOLOGY 9 (ST9) SOLAR SAIL MISSION

The FDAB continues to be very active in the New Millennium Program (NMP) Space Technology-9 (ST9) Solar Sail technology validation mission concept studies. The FDAB is working closely with the GSFC Solar Sail team, the MSFC In Space Propulsion team, JPL, and LaRC in defining Attitude Control Systems (ACSs) that use standard and sail actuator systems. The FDAB also developed and validated a low-fidelity coupled ACS and orbit simulator to trade controllability with orbit maneuvering. With heavy FDAB support, the teams are developing solar sail validation and verification concepts, and addressing any scalability concerns for various Earth orbit missions.

The FDAB also developed detailed mission design concepts for a Sun-synchronous “dawn-dusk” mission orbit. Several orbit utilities were developed in order to accomplish this. The first utility developed was a Satellite Tool Kit (STK)/Astrogator script used in conjunction with Astrogator’s custom propagator plug-in capability and the second utility was a Matlab-based low-thrust preliminary mission design tool developed in conjunction with the Mission Applications Branch at the GSFC.

[Technical contacts: Steven Cooley and Dave Mangus]

3.10 TERRESTRIAL PLANET FINDER (TPF)

http://planetquest.jpl.nasa.gov/TPF

The Terrestrial Planet Finder Coronagraph (TPF-C) is one of the current concepts for detecting and characterizing extrasolar planets orbiting nearby stars. The coronagraph instrument is a space-based observatory with 8 m×3.5 m primary mirror that aims to reject the starlight and detect the reflected planet light in the visible range. Dynamic jitter, introduced by environmental and onboard mechanical disturbances, degrades the optical performance (image quality) and the capability to reject starlight (contrast ratio). The TPF coronagraph must maintain the dynamic stability of its instrument to the sub-

milliarcsecond and nanometer level in order to successfully perform contrast imaging required for planet detection. Meeting these stringent stability requirements in the presence of dynamic jitter imposes significant technical challenge on the pointing and vibration isolation systems.

During FY05, the flight baseline 1 (FB1) design was developed for performing structure, thermal, and dynamic analyses. For the FB1 design, the pointing control system (PCS) team has created two vibration isolation schemes: passive and active. The passive isolation system features a two-stage isolation design. The first stage isolates the reaction wheel assembly, one of the major disturbance sources, from the spacecraft support module, while the second stage isolates the payload from the spacecraft. This design uses flight-proven mechanical components (flexures and damping mechanisms) and does not require additional actuators/sensors operating during observation. The active isolation system is based on the disturbance free payload (DFP) design developed at the Lockheed Martin Advanced Technology Center. The DFP technology achieves isolation through nearly complete separation between the payload and spacecraft support module, and uses interface sensors and actuators to provide inertial pointing and maintain proximate separation of the bodies. The PCS team plans to carry both passive and active isolation systems through various design iterations and thoroughly understand the cost and risks related to each system before down-selecting an isolation system for TPF-C.

The PCS team has also built an integrated dynamic model in order to verify that the predicted jitter performance satisfies the current error budget. These benchmark results demonstrate that a properly designed system can meet the stringent performance requirements for TPF-C. A number of activities have been planned to enhance the current design and analysis:

- Control system optimization (of the loop shaping designs as well as a modern optimal control system)
- Parameter uncertainty, including variability in critical structural stiffnesses
- Update time simulation models to include more accurate actuator and sensor models

[Technical contact: Kuo-Chia (Alice) Liu]

3.11 VENUS SOUNDER FOR PLANETARY EXPLORATION (VESPER)

The FDAB is supporting a Discovery Proposal for a Venus mission, VESPER (Latin for evening star), led by GSFC Laboratory for Extraterrestrial Physics. VESPER will integrate key measurements with atmospheric models to investigate the coupled processes of chemistry and dynamics in the Venus middle atmosphere; the VESPER goal is to conduct a tightly focused study of the Venus atmosphere as part of a larger NASA program of comparative planetology. VESPER consists of a spacecraft and an atmospheric entry probe. The FDAB has analyzed launch vehicle and spacecraft requirements, generated nominal trajectory data, analyzed potential probe impact locations, and coordinated navigation analysis for the nominal 2011 launch opportunity.

[Technical contact: Greg Marr]

4.0 TECHNOLOGY DEVELOPMENT

4.1 ATTITUDE DETERMINATION AND SENSOR CALIBRATION

The purpose of the advanced attitude determination and sensor calibration task is to improve the accuracy and efficiency of both processes taking in account current and future mission requirements, as well as to disseminate the analysis and provide consultation. This fiscal year, algorithms were developed to better estimate attitude for spinning spacecraft. In the past, the requirements on spinning spacecraft ground attitude systems did not require the sophisticated algorithm developed required for three-axis stabilized missions. Within the next two years, two missions consisting of spinning spacecraft, THEMIS, and ST-5 will launch with modest attitude sensors, but with challenging attitude determination requirements. In many respects, spinning spacecraft attitude estimation and sensor calibration now require equal, if not more sophisticated, algorithms developed than those of three-axis stabilized missions. The ground attitude estimation approach was worked on this year. Over the past year, two filters have been developed and incorporated into our operational system to accomplish this estimation task: the Markley variable Extended Kalman Filter (EKF) and the Unit Vector Filter (UVF). The Markley variable filter consists of seven states including angular momentum in the inertial frame, angular momentum in the body frame, and a rotation angle. The UVF is an EKF that estimates attitude and rate errors which are then resolved into an attitude quaternion and spacecraft rate. Both filters had comparable accuracies, quick convergence times, and were stable. The UVF did have the advantage of quicker execution time. Both filters now provide a mechanism for highly accurate attitude and rate estimation, even for the most dynamic scenarios.

The second goal of the advanced attitude determination task is to improve the calibration accuracy of spinning spacecraft sensors. A prototype of this calibration system is planned for the end of this year. To date, a magnetometer calibration system has been tested using flight data from the Fast Auroral Snapshot Explorer (FAST) mission and incorporated into our operation system. It solves for magnetometer scale factors and biases. The alignment portion will be added to the comprehensive prototype mentioned above.

The third goal of this task is to improve the overall process efficiency of ground attitude estimation and sensor calibration. To this end, the task will be tweaking the Multimission Spin Axis Stabilized (MSASS) software system to enable automation using external programs and scripting. In addition, the sequential Davenport gyro calibration algorithm will be modified later this year to enable real time gyro calibration either on the ground or onboard the spacecraft.

Lastly, this task has disseminated various written technical reports on spacecraft attitude estimation and sensor performance, as well as consultation. In particular, the task published the following papers: “Image Sensor Alignment Estimation,” “Spinning Spacecraft Kalman Filter,” “Vibrations and Sensor Noise,” and an updated version of the “Spacecraft Attitude Determination Accuracy from Mission Experience.” The task also provided consultation to a variety of current and future missions.

[Technical contact: Richard R. Harman]

4.2 NAVIGATION TECHNOLOGIES

4.2.1 Global-Positioning-System-Enhanced Onboard Navigation System (GEONS)

http://geons.gsfc.nasa.gov

Two new releases of GEONS and associated utilities were completed. Release 2.3 delivers TDRSS one-way (forward-link) Doppler measurement capability, improvements in ionospheric delay modeling, and new reset commands. Release 2.4 delivers an update to the gravity process noise models providing improved usage flexibility, and capability for integrating the spacecraft state using high-order lunar gravity. Design work was completed on Release 2.5, which early in the next fiscal year will deliver compliance with ongoing GPS system modernization (additional frequencies and signal structures), new bias models, and full restart capability.

[Technical contact: Russell Carpenter]

4.2.2 GEONS Ground Support System (GGSS)

The GSFC Flight Dynamics Analysis Branch (Code 595) is developing a ground support system for the GEONS. The GEONS Ground Support System (GGSS) will provide a means for calibrating the onboard system, assessing the quality of the onboard navigation solutions, monitoring the performance of the system over time, and distributing the associated flight dynamics products. The GGSS incorporates the GEONS software for ground processing and is compliant with the Goddard Mission Services Evolution Center (GMSEC) Bus architecture. To date, Build 1 has been developed, which includes the Ground Test Program and Graphical User Interface for GEONS allowing easy set-up and runs of user-defined scenarios in GEONS.

[Technical contact: Bo Naasz]

4.2.3 GPS-Based Navigation for High Earth Orbits

GSFC has been a leader in expanding the utility of the Global Positioning System (GPS) for spacecraft navigation in High Earth Orbits. During 2005, the branch completed a major hardware in-the-loop testing effort to assess the real-time orbit determination accuracy of GPS-based navigation in a number of different high Earth orbital regimes, and supported the first performance testing of the Goddard-developed Navigator GPS receiver in Geostationary orbit. Two papers were published on these efforts.

The hardware in-the-loop testing was conducted in GSFC's Formation Flying Test Bed (FFTB), a facility that integrates GPS receivers, NASA's GEONS extended Kalman filter software, and telemetry and commanding interfaces in a manner very similar to how these systems would be integrated on a spacecraft flight computer. Measurements collected from a GPS receiver (connected to a GPS radio frequency (RF) signal simulator) were processed in the GEONS navigation filter in real time, and resulting errors in the estimated states were assessed. The study also makes direct comparisons between the results from the above hardware in-the-loop tests and results obtained by processing GPS measurements generated from software simulations. This provided a means to further validate the clock models, measurement noise parameters, and other error settings used in software simulations of orbit determination performance conducted at GSFC. The Position-Velocity-Time (PiVoT) GPS receiver, developed by GSFC in the late 1990s, was used in these tests. For the most challenging orbit simulated, a 12 h Molniya orbit with an apogee of approximately 39,000 km, mean total position and velocity errors were approximately 7 m and 3 mm/s respectively. Comparisons made between the real-time results and those obtained by processing software simulated measurements showed good agreement. The study provided some valuable insights into how accurately our software measurement, clock, and other error models represent the true errors present in real measurements, and has helped to validate many of the settings and assumptions used in these software simulations.

The Branch also provided significant support to the Hardware and Component Systems Branch for the software development and initial testing of the new, Navigator GPS receiver. The Navigator GPS receiver was developed as a fully radiation hard, space qualified GPS receiver with special acquisition and tracking capabilities suitable for high altitude orbits. The receiver has approximately 10 dB of improved acquisition sensitivity by extending the correlation interval to the full GPS data bandwidth, 20 ms. The Fast Fourier Transform (FFT) based acquisition engine allows extremely rapid signal acquisitions of only a few seconds, providing a robust cold-start capability. The increased sensitivity is critical for high altitude applications where GPS observability is poor; it allows the receiver to acquire and track many more GPS signals than would be available to a conventional receiver. Furthermore, the GEONS navigation filter is integrated in the receiver. The receiver has been tested extensively in a simulated geostationary orbit. Using a 10 dB receiving antenna and assuming no GPS constellation or ionosphere errors, orbit accuracies on the order of 10 m Root Mean Squared (RMS) have been obtained. Additional tests are being conducted with the Navigator in simulated highly elliptical orbits under consideration for the Magnetospheric Multiscale Mission (MMS), with low perigee altitudes, but apogees ranging from 12 to 31 Earth Radii.

[Technical contact: Mike Moreau]

4.2.4 Lunar Navigation Concepts

Development of the Exploration Architecture has crossed many disciplines and evolved into several task groups. Analysts from FDAB had roles on the Space Communications Architecture Working Group (SCAWG) and the Command, Control, Communications, and Navigation Concept of Operations (C3N ConOps) working group. FDAB supported the SCAWG navigation team with analysis on the efficiency of possible lunar navigation constellations and the effects of the different constellations on lunar surface users. Results for the Lang and Meyer constellation are shown in Figure 4-1. FDAB also developed a white paper on figures of merit for navigation. FDAB provided all navigation analysis and input to the C3N ConOps. Both the SCAWG Report and the C3N ConOps will be used as input to the requirements for the navigation architecture for exploration.

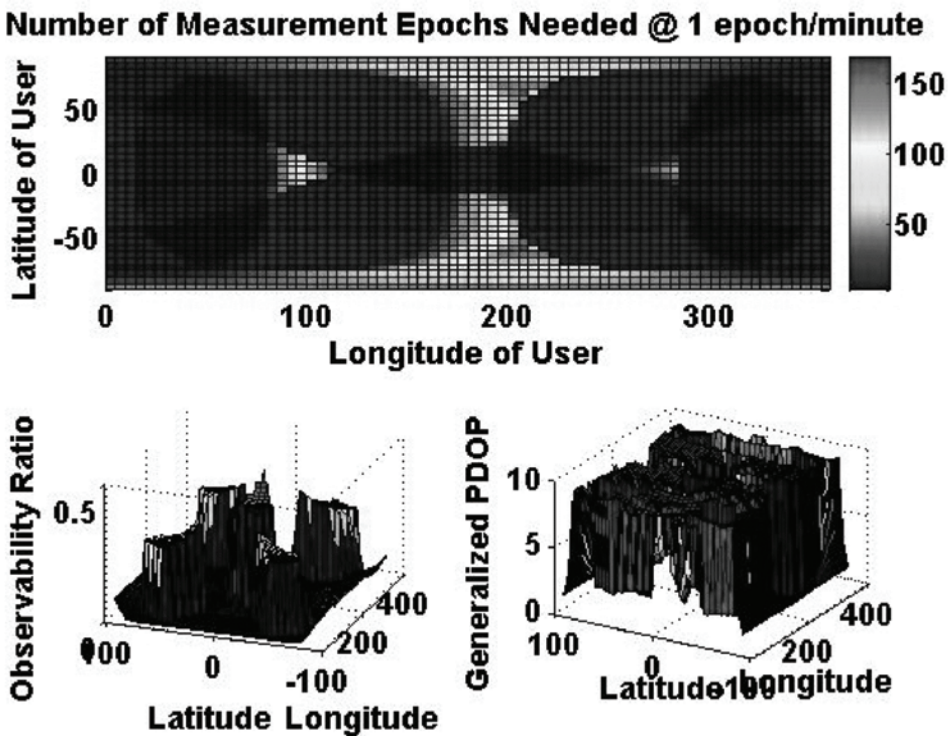

Figure 4-1. Analysis of Lang and Meyer Constellation

[Technical contacts: Russell Carpenter and Cheryl Gramling]

4.3 FORMATION FLYING TECHNOLOGY

4.3.1 Optimal Formation Flying Orbit Design

One of the most interesting and challenging aspects of formation guidance law design is the coupling of the orbit design and the science return. The analyst's role is more complicated than simply to design the formation geometry and evolution. He or she is also involved in designing a significant portion of the science instrument itself. The effectiveness of the formation as a science instrument is intimately coupled with the relative geometry and evolution of the collection of spacecraft. The science return can be maximized, therefore, by optimizing the orbit design according to a performance metric relevant to the science mission goals. We have developed a simple method for optimal formation guidance that is applicable to missions whose performance metric, requirements, and constraints can be cast as functions that are explicitly dependent upon the orbit states and spacecraft relative positions and velocities. The approach employs a general form for the cost and constraint functions, and we have derived their semianalytic gradients with respect to the formation initial conditions. The gradients are broken down into two types. The first type are gradients of the mission specific performance metric with respect to formation geometry. The second type are derivatives of the formation geometry with respect to the orbit initial conditions. The fact that these two types of derivatives appear separately allows us to derive and implement a general framework that requires minimal modification to be applied to different missions or mission phases. This approach has been successfully applied in support of two missions: the Magnetosphere Multiscale Mission (MMS), and the Laser Interferometer Space Antenna (LISA).

[Technical contact: Steve Hughes]

4.3.2 Optimal Formation Maneuvers

In support of numerous formation flying missions, we have developed a method to solve the impulsive minimum fuel maneuver problem for a distributed set of spacecraft. The method assumes a nonlinear dynamics model and is applicable to multiple flight regimes including low-Earth orbits, highly-elliptical orbits (HEO), Lagrange point orbits, and interplanetary trajectories. Furthermore, the approach is not limited by the interspacecraft separation distances and is applicable to both small formations, as well as large constellations. Semianalytical derivatives have been derived for the changes in the total ΔV with respect to changes in the independent variables. We have also developed the ability to apply a set of constraints to ensure that the fuel expenditure is equalized over the spacecraft in formation.

[Technical contact Steve Hughes]

4.4 ADVANCED MISSION DESIGN TECHNIQUES

4.4.1 Creation of First-Guess Utilities to Support Development of Lunar Architectures

The FDAB continued a major effort this year to create first-guess utilities for cislunar, libration point, and other multibody orbits in order to increase both the efficiency and capability of the mission design process. The utilities will be used to help develop possible lunar architecture concepts as part of the Exploration Vision.

The knowledge of the properties of multibody orbits, such as those within cislunar space, is necessary for the development of an exploration infrastructure. For example, the use of Halo orbits, which are periodic solutions of the circular restricted three body problem (CRTBP), can be used to obtain communication and navigation capabilities for satellites and/or lunar structures on the far side of the moon. The ability to thoroughly characterize the entire family of these Halo orbits, as well as numerous other types of orbits, will result in a much more capable and efficient mission design process.

This year, the FDAB, in collaboration with Professor David Richardson of the University of Cincinnati, developed analytical approximations for Halo orbits in both the Sun–Earth and the Earth–Moon systems. The FDAB also generated analytical approximations for the “Figure-8” libration point orbits. Next year, the FDAB plans to investigate the possibility of developing analytical approximations for the “Moon-Wrapping” orbits shown in Figure 4-2 (numerically generated by another FDAB collaborator, Dan Grebow of Purdue University) below. The algorithms developed as part of this effort will be of great use in helping to analyze possible mission orbits for various lunar architecture concepts.

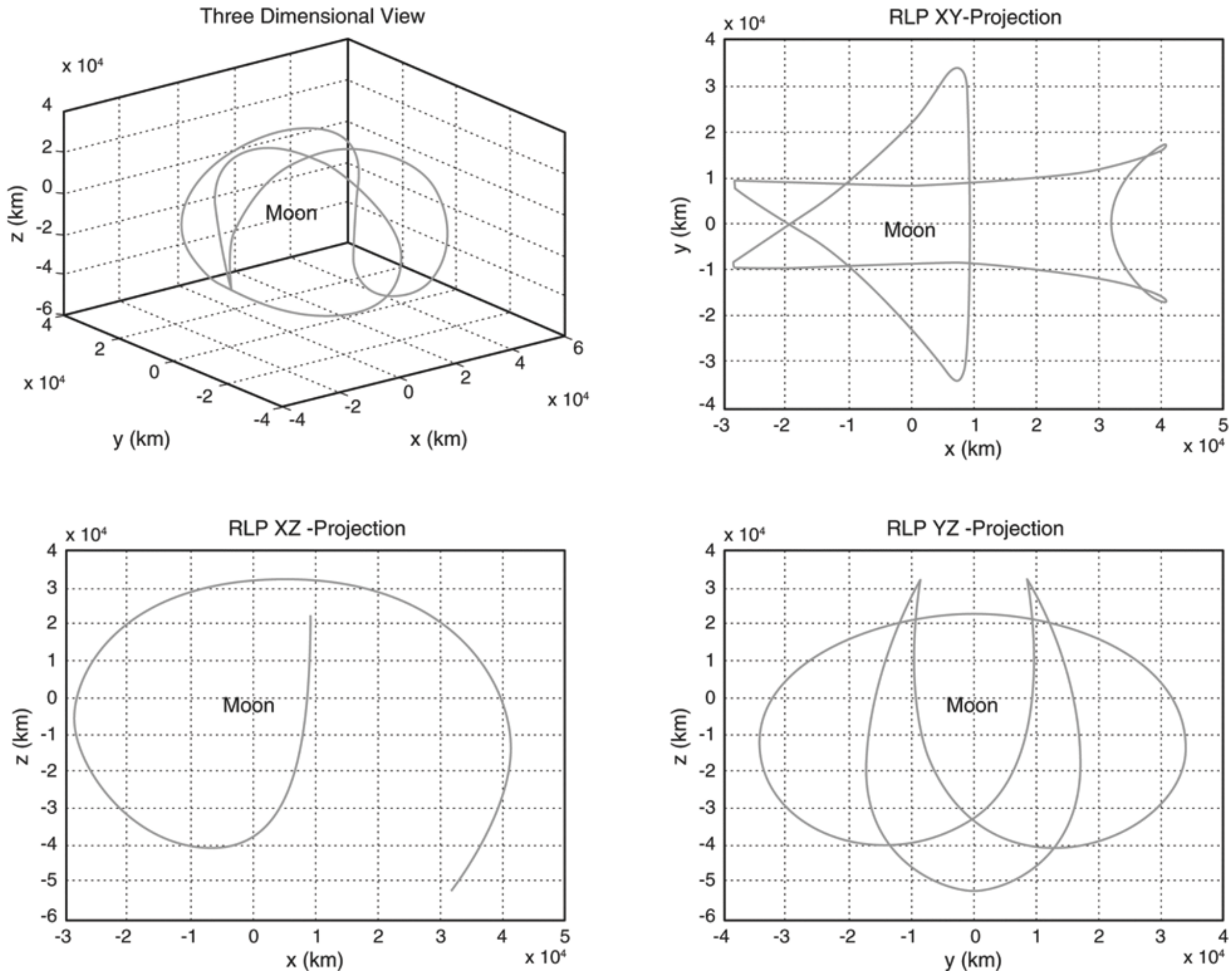

Figure 4-2. Sample Moon-Wrapping Orbits

[Technical contact: Steven Cooley]

4.4.2 On-Orbit Staging (OOS)

FDAB personnel have been working on developing the concept of On-Orbit Staging (OOS) to enable the accomplishment of some of the more challenging goals of the Vision for Space Exploration (VSE). OOS extends the implementation of ideas originally put forth by Tsiolkovsky, Oberth, and Von Braun to address the total mission design by applying the basic staging concept to all major trajectory maneuvers. Utilization of OOS, in combination with propellant and supply depots strategically placed at trajectory nodes, can substantially reduce the propulsive resources required for high-energy space missions while simultaneously enabling larger payloads. Analysis of several hypothetical Mars mission concepts has shown that OOS can reduce the resources required for, or increase the payloads of, these missions up to an order of magnitude over the current "single-stage" propulsion architecture.

FDAB personnel have participated in briefings to GSFC Center management, and personnel from NASA Headquarters up to and including the Administrator, in which the OOS concept has been favorably received. Briefings to Exploration Mission Systems Directorate (EMSD) personnel and discussions about the possible applications of OOS to the VSE are in the works.

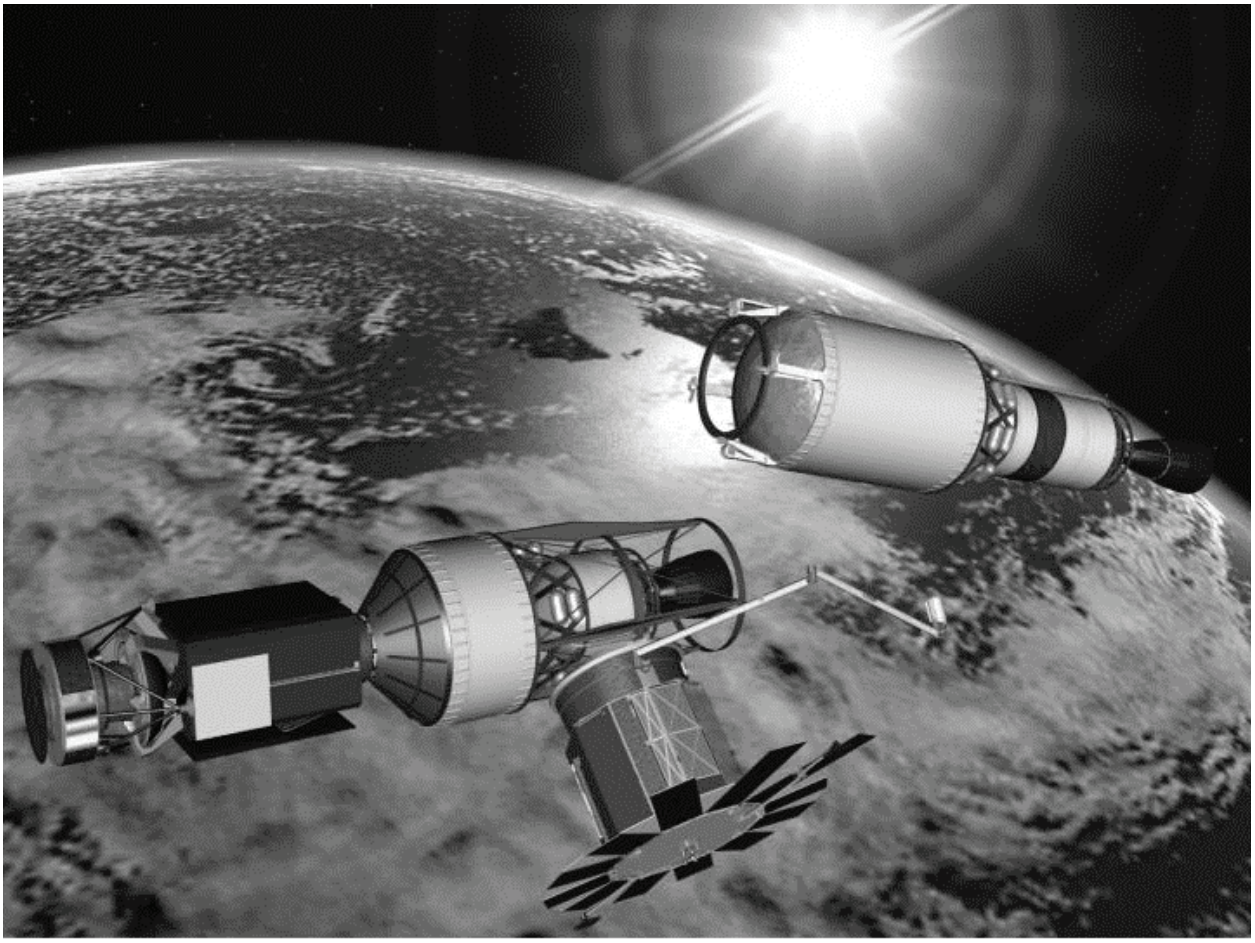

Figure 4-3. Low Earth Orbit Components of On-Orbit Staging

[Technical contacts: Dave Folta and Frank Vaughn]

4.4.3 Trajectory Optimization

The FDAB continued to develop tools to optimize satellite trajectories. This year, we developed a method to solve the impulsive minimum fuel maneuver problem for a distributed set of spacecraft in multiple flight regimes including low-Earth orbits, highly-elliptical orbits (HEO), Lagrange point orbits, and interplanetary trajectories. The method uses “patch-points,” which break up a candidate trajectory into discrete points combined with the use of semianalytical derivatives describing how the total ΔV changes with respect to a change in the position or time of the patch points. The method also applies a set of constraints to ensure that the fuel expenditure is equalized over the spacecraft in the formation. The method was successfully applied to two proposed formation missions, the Magnetospheric Multiscale Mission (MMS) and the Laser Interferometer Space Antenna (LISA) mission.

[Technical contacts: Steven Hughes and Steven Cooley]

5.0 BRANCH INFRASTRUCTURE

5.1 BEST PRACTICES FOR ORBIT ANALYSIS, DESIGN, NAVIGATION, AND CONTROL

In the aftermath of the release of the report by the Columbia Accident Investigation Board, many organizations have begun an effort to identify and record practices essential to mission success. These practices will be verified by project review boards as having been followed. The Flight Dynamics Analysis Branch began documenting its practices in 2004 by describing in writing what was already being done as a matter of course.

All phases of spaceflight missions are covered, from preliminary mission analysis to spacecraft end of life. For the mission operations phase, we recommend AIAA's "Satellite Mission Operations Best Practices," April 2003, available at:

<http://www.aiaa.org/tc/sos/bp/Ops_Best_Practices.PDF>.

Our set of best practices includes topics that arise during mission development, earlier than those addressed in the AIAA document, although we also include some operations topics. Our Best Practices document will be expanded as new experiences provide new insights and as growing familiarity with the document identifies practices overlooked in the text but followed, nevertheless.

[Technical contact: Charles Petruzzo]

5.2 COMMERCIAL-OFF-THE-SHELF (COTS) SOFTWARE MANAGEMENT

The Flight Dynamics Analysis Branch successfully brought the ESMO, SSMO, and IMDC Projects together to create a consolidated set of licenses for the COTS tool Satellite Toolkit. This mission analysis software has become an integral part of the Mission Operations Center ground systems for Aqua, Aura, Terra, and other ESMO missions; Microwave Anisotropy Probe (MAP) and Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), and the Small Explorer (SMEX) satellites; as well as the FDF product generation for many missions. It is used by the FDAB for operational and future mission flight dynamics analysis and by IMDC engineers for many types of study mission analyses. The STK License Consolidation enabled the projects and missions involved to take advantage of the 35% volume discount the vendor offers and decreased the number of procurements for STK software. The Consolidated Licenses upgraded all licenses to network versions, to facilitate not only sharing licenses, but also to enable quick reassignment of licenses as the needs changed. Fifty-five STK Professional/ packages were upgraded and renewed, and various other modules were purchased, renewed, and upgraded. The number of overall licenses being used by the groups was decreased by ~10, while capabilities not available to some of the organizations were made available to all.

The original plan was to network all of the products with one main server location. Because Information Technology (IT) Security requirements prevented open network servers accessing closed network servers (such as operational MOC servers), the concept of two server locations, one for closed and one for open, was chosen. The MESA Lab in Bldg. 11 maintains the open network licenses, based on its history of maintaining the 30 networked licenses used by the FDAB and other MESA engineers. The FDF in Bldg 28 has begun the process of building the closed network servers, and has successfully enabled sharing licenses between the SMEX MOC and the FDF.

[Technical contact: Karen Richon]

5.3 ORBIT DETERMINATION (OD) TOOLBOX

The OD Toolbox is an OD analysis tool set based on Matlab and Java, which provides a much more flexible way to perform early mission analysis than is possible with legacy tools. Matlab is the primary user interface, and is used for implementing new measurement and dynamic models from a library of base classes, rather than making a major software change every time a new mission proposal comes up, particularly one that implements new flight dynamics technologies. The OD Toolbox uses extensions of the Java Astrodynamics Toolbox (JAT) as an engine for routines that might be slow or inefficient in Matlab, like high-fidelity trajectory propagation, lunar and planetary ephemeris lookups, precession, nutation, and polar motion calculations, ephemeris file parsing, etc. The tool set primarily serves the needs of conceptual mission studies, which are frequently performed for proposals, the IMDC, and during Phase A of approved missions. We expect that as it matures, it will also be of particular utility to formation flying and exploration missions, which make extensive use of novel combinations of onboard sensors. A key element of the effort is the extension of the GMSEC middleware-based architecture to domains outside of mission operations and ground systems development and integration. The OD Toolbox is designed to "publish and subscribe" to a GMSEC-compliant "software bus," to enable the exchange of data with other flight dynamics tools, such as GMAT.

The objectives for development spirals zero and one were completed. Highlights include detailed validation of the Java Earth orbit propagation models against STK and Freeflyer. The Java force models may be used with either Java integrators or Matlab integrators, and the Java integrators may call Matlab force models.

[Technical contact: Russell Carpenter]

5.4 GODDARD MISSION ANALYSIS TOOL (GMAT)

The General Mission Analysis Tool (GMAT) is a software system under development by GSFC in collaboration with the private sector. The project is in the second year of the development phase, and we are currently performing acceptance tests in order to prepare GMAT for an intended open source release in early 2006.

GMAT was developed for many reasons. Some of the most important are to provide a development approach that maintains involvement from the private sector and academia, encourages collaborative funding from multiple government agencies and the private sector, and promotes the transfer of technology from government funded research to the private sector. There are also many technical motivations that GMAT is intended to address and they are discussed below

GMAT was designed and developed to provide many capabilities not provided by other mission analysis systems. For this reason, GMAT has been developed to be fully platform independent. Both the Graphical User Interface (GUI), and the GMAT engine, are being built and tested on Windows, Macs, and Linux. GMAT was designed for intuitive use from both the GUI, and a script language similar to that of Matlab. The propagation capabilities in GMAT allow for fully coupled dynamics modeling of multiple spacecraft, in any flight regime. Other capabilities in GMAT include user definable coordinate systems, 3-D graphics in any coordinate system GMAT can calculate, 2-D plots, branch commands, solvers (and soon optimizers), GMAT functions, planetary ephemeris sources including DE405, DE200, SLP and analytic models, script events, impulsive and finite maneuver models, and many more.

We are currently performing acceptance testing of the system. An extensive set of tests cases have been developed. Over 100 different propagation test cases have been developed and performed using a suite of

force models for the Earth and planets. We have used many software systems such as STK, FreeFlyer, and Swingby as truth models. Calculation parameters in different coordinate systems and with respect to different central bodies are also being tested. The testing architecture is fully automated and permits testing of new executables with ease.

[Technical contacts: Steven Hughes and David Folta]

5.5 PYXIS TOOL

Pyxis is a prototype first-guess utility for the design of multiple encounter interplanetary trajectories. It takes a very graphical mouse-oriented approach. The calculations use simple patched conics, although the planetary positions are taken from a DE405 file. In using Pyxis, the user first selects a departure body (usually Earth) and an arrival body. A 'Pork chop' plot window is displayed, from which the user may select departure and arrival dates. Then a 'Flyby' plot window of the arrival body is displayed, which will show possibilities for future flybys. One of these may be selected, or alternately a deep space burn may be scheduled, as displayed in a 'Deepburn' window. This process may be repeated indefinitely. When the process is complete, a session may be saved, or a script for STK, GMAT, or Argosy may be generated.

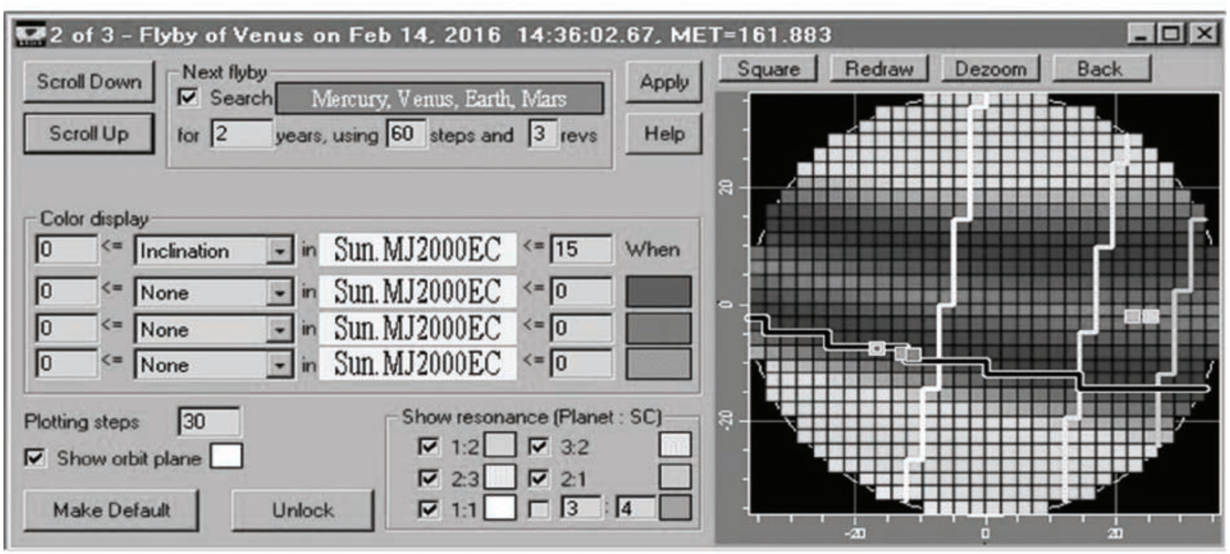

Figure 5-1. Pyxis Tool Flyby Window

A typical flyby window is displayed in Figure 5-1. It is divided into a dialog section on the left, and the actual flyby plot on the right. The first thing to notice is that the flyby plot is a circle. The center is no bend in the trajectory—a flyby at a very large distance. The area near the circumference is maximum bend—a flyby very close to the surface of the planet. In this case, the maximum bend angle is about 36º. This will change with different planets and different velocities.

The pixels are color-coded to show a property of the orbit after the flyby. In this example, the colors correspond to ecliptic inclination. The jagged vertical lines resonances with the flyby planet, and are also color-coded. The code is shown in the lower left corner of the dialog portion.

The jagged black line indicates trajectories that remain in the orbital plane of the Flyby planet. Occasionally along this line will be seen non-resonant re-encounters of the flyby planet, which are only possible after more than one orbit. In this case three are visible as colored squares with a white border. The brighter ones indicating sooner flybys. These occur at approximately 1.5, 2.5, and 3.5 orbits of the spacecraft. Encounters with other planets are also displayed. Here, Earth encounters are displayed in the upper right area as two green dots. The brighter dot is the earlier encounter (322 days) and the other one is later (680 days).

[Technical contact: John Downing]

5.6 BRANCH STRATEGIC PLANNING

http://fdab.gsfc.nasa.gov

The Flight Dynamics Analysis Branch is currently drafting a Strategic Implementation Plan to support the Branch's participation in NASA's accomplishment of the NASA Strategic Plan. The following is an outline of the Branch development process, a timeline for draft completion, and follow-on activities to implement any changes, recommendations, or actions developed through the planning process.

Strategic Implementation Plan (SIP) Development Elements and Format
The FDAB SIP will include the typical elements:
Vision Statement
Mission Statement
One or more Strategic Goals
Strategic Objectives (as necessary)
Charter for Road-mapping and implementation activities

To date, the SIP team has convened to develop a Vision and Mission Statement for the FDAB SIP. The statements were developed with the following guidance in mind.

Vision Statement
A vision statement is a business' guiding image of success, formed in terms of their contribution to society. It is a more emotionally-derived statement that elicits a visual image of the company's destination. The key issues addressed by the vision statement are:

- Who we are
- What we do
- Where we are going
- What guiding principles characterize our effort

Mission Statement Element
A mission statement is defined as a business' guiding principles that state what the company's goals are, what their values are, and where they are headed. A mission statement is a written, easy-to-remember sentence, short list of bullet points, or paragraph illustrating a business' goals and purpose. A mission statement identifies the facility to its customers, vendors, the media, and others that will be using or requiring its services or products. Key factors that may be considered in the development of a mission statement are:

- Statement of Purpose
- Statement of Strategy
- Statement of Value
- Statement of Behavioral Standards
- Statement of Character

The team is continuing with development of strategic goals, and then will develop, as deemed necessary, strategic objectives to further outline a strategy for goal achievement. This process will provide the branch with a document outlining a high-level management strategy for the next 10–20 years. This document is targeted for completion by the end of November 2005.

At that time, subject-or functional-area specific teams will be chartered to address methods and processes required for achievement of the plan. This is typically one of the larger addendums to the SIP, and will take considerable effort in development. This is the area in which the organization will identify the process, skills, competencies, resources, and technologies that will be used to achieve the strategic goals. This process is targeted to begin in January 2006, and is expected to be completed by May 2006.

[Technical contact: Mika Robertson]

5.7 SCHATTEN SOLAR FLUX PREDICTIONS

http://fdf.gsfc.nasa.gov/

The Flight Dynamics Analysis Branch provides a number of services that require long-term prediction of solar activity. In particular, solar flux predictions are required for accurate, long-term prediction of satellite orbits, and orbit decay rates in low altitude orbits.

The FDAB continues to support and use solar flux prediction provided by Dr. Kenneth Schatten's models. Dr. Schatten employs a physically based method known as a solar precursor method, to predict the mean solar flux for the upcoming solar cycle. This method uses direct and indirect measurements of the Sun's polar magnetic fields near the minimum of the 11-year solar flux cycle, and solar dynamo theory to estimate the solar activity during the remainder of the cycle. Recent reviews of Schatten's methods by solar physicists at NASA's Goddard Space Flight Center have confirmed Schatten as the best available resource for long-term prediction of solar activity.

The Sun is currently approaching the minimum of cycle 23, making the upcoming months and years the prime time for prediction of solar activity for cycle 24. Schatten's latest prediction, in concurrence with predictions from numerous other solar physicists, forecasts solar cycle 24 to be among the smallest cycles in recent history.

[Technical contacts: Bo Naasz and Kevin Berry]

6.0 EMPLOYEE DEVELOPMENT

6.1 NEW EMPLOYEE PROFILES

Neerav Shah joined the FDAB on June 27, 2005. After receiving a B.S. degree in Aerospace Engineering from Pennsylvania State University in 2003, Neerav joined the NASA Glenn Research Center (GRC) as a Control Systems Engineer in the Controls and Dynamics Branch. At GRC, Neerav developed a simulation test bed to validate various advanced control techniques for aircraft jet engines, led efforts to investigate his branch's role in nuclear propulsion, and investigated applying discrete event control to aircraft propulsion systems. Prior to joining NASA after graduating from Penn State, Neerav was employed as a co-op student at the U.S. Naval Research Laboratory where he worked on developing orbit determination tools for the Navy. Neerav completed his last co-op rotation at GRC where he conducted testing and validation of PITEX, an integrated vehicle health monitoring system. Neerav will be applying his simulation and controls background in his new position with the FDAB. Currently, he is supporting the Constellation-X mission study. He has supported colleagues in developing a system simulation in Matlab's Simulink environment, and is now leading the development of the simulation in a C-based environment developed in-house, called Freespace. The Freespace simulation development will yield faster performance, as well as a set of tools that can be used for future missions. In addition, Neerav is a member of the ST-5 Guidance Navigation and Control (GN&C) team, where he will provide ground support during the ST-5 mission. Neerav plans on pursuing a graduate degree in Aerospace Engineering from the University of Maryland with a focus on controls and dynamics of spacecraft beginning in early 2006.

Linda Kay-Bunnell joined the FDAB on March 7, 2005. After receiving a B.S. degree in Aerospace Engineering from Florida Institute of Technology in 2000, she attended the George Washington University's Joint Institute for Advancement of Flight Sciences at NASA Langley Research Center (LaRC) where she received her M.S. degree in Aerospace Engineering in 2003. As a student and then as an employee at LaRC, Linda's work involved orbit determination and trajectory analysis in support of NASA's Revolutionary Aerospace Systems Concepts (RASC) program, and various studies directed by NASA's Space Architect in support of the Vision for Exploration. As a new employee at GSFC, she is being introduced to aspects of space operations as co-task monitor for the FDF Maneuver Support Task, and as a member of the ST-5 Maneuver Operations Team. Linda is also currently providing trajectory design analysis for the Inner Heliospheric Sentinels Spacecraft System mission study.

Philip Calhoun joined the FDAB on May 30, 2005. Phil received a B.S. degree in Mechanical Engineering from the University of Tennessee in 1988, where he participated as a co-op student at NASA Marshall Space Flight Center (MSFC). After transferring to NASA LaRC in 1998, Phil received his M.S. degree in Mechanical Engineering from the University of Alabama in Huntsville in 2001. At LaRC, he performed design and analysis of entry vehicle flight controls for both Earth and Mars systems, including the Mars Science Laboratory. Prior to working at Langley Phil worked at the MSFC in the Precision Control Branch. There he contributed to the design and analysis of attitude control systems for Earth orbiting spacecraft. Among these were Gravity Probe-B and the Advanced X-ray Astrophysics Facility—Imaging (AXAF-I). Phil will be applying his knowledge of spacecraft attitude control design and analysis in his new position with the FDAB. Currently, he is responsible for design and analysis of the Observing mode for the Lunar Reconnaissance Orbiter (LRO). He has performed preliminary algorithm design and mid-fidelity simulation studies of the Lunar Nadir and off-Nadir sub-modes, as well as analysis to support pointing error budgets. Phil supported the LRO team in a recent presentation of their attitude control design to a peer review panel. His ongoing work includes refining the observing mode design, analysis, and pointing error budgets as the LRO configuration matures, as well as defining and implementing a slosh dynamics analysis plan.

Edwin Dove originally joined the FDAB in January of 2004 as a Co-op on a one year tour of duty. In May 2005 Edwin graduated from Penn State with a B.S. degree in Aerospace Engineering, and in July 2005, he started his full-time career in the FDAB. As part of the transition to full-time status, Edwin began his Professional Intern Program (PIP) I project under the supervision of Steve Hughes. His PIP I project involved the testing of the General Mission Analysis Tool (GMAT), collaborating with the GMAT development team in order to improve the program's functionality, using GMAT to solve relevant missions supported by FDAB, and documenting test results of GMAT.

6.2 PROFESSIONAL INTERN PROGRAM (PIP)

The PIP is a developmental program designed to acquaint entry-level professionals with NASA and GSFC missions and operations, integrate them into the workforce as quickly as possible, and prepare them for more complex and responsible duties that they can perform with increasing independence. Required program activities include an Individual Development Plan (IDP) prepared for each intern by the supervisor, establishment of a mentor relationship with an experienced staff member, various orientation activities, formal and on-the-job training, and completion of a PIP project, which the intern describes in a written report and oral presentations given in Levels I and II to a panel of evaluators.

PIP Level I : James Webb Space Telescope (JWST) Trajectory Design (Leigh Janes)

The JWST is an infrared space telescope currently scheduled to launch in 2011. Because of instrument requirements, the telescope and science instruments must be shielded from the light of the Sun, Earth, and Moon. In order to keep these three objects in the same direction from the spacecraft, JWST will reside in an orbit about the Sun–Earth second Lagrange point (L2).

The objective of this PIP project was to determine possible launch windows for JWST. At the beginning of the analysis mission requirements for the orbit stated that the spacecraft would remain in a Sun-Earth L2 orbit and that no lunar and Earth eclipses were allowed during the mission. In order to narrow down possible launch opportunities, every day of the year 2011 was examined to see if 10-year trajectories around L2 were achievable. For each day of the year, the search began for a noon launch time. Other launch times spaced 30 minutes apart were checked to see if the 10 year trajectory requirement was met. Once all of the data was generated, the launch window was reduced.

The reduced launch window eliminated cases with lunar and Earth eclipses, cases larger than an 800,000 km excursion in the Rotating Libration Point (RLP) Y direction, and cases that failed the first Mid-Course Correction requirement. This PIP project resulted in establishing possible launch windows for the current flight profile, as well as assisting the JWST Orbit Trade Working Group in suggesting new orbit size mission requirements.

(Leigh Janes has been a full-time Goddard employee since July 2004. Prior to that time, she was a co-op student within the Branch. She received her B.S. degree in Aerospace Engineering from Purdue University.)

PIP Level I : Modeling THEMIS Orbit Maneuvers Using Hydrazine Propulsion (Kevin Berry)

The main objective of the THEMIS mission is to study the magnetosphere of the Earth. In particular, it will be focusing on auroral substorms in order to learn more about the driving forces behind the Aurora Borealis. The mission consists of four spinning probes (+1 spare) arranged into three different orbits with

the requirement that they must all be collinear during the auroral substorms. To accomplish this goal, orbits were chosen with periods of 1 day, 2 days, and 4 days with the extra probes stored in the 1 day orbit. All five THEMIS probes are planned to be launched on a single launch vehicle in October 2006.

The goal of this project was to validate the impulsive maneuver sequence designed by the principal investigators at University of California at Berkeley (UCB) against a finite engine model designed in General Maneuver Program (GMAN). GMAN is one of Goddard's most accurate maneuver tools and has been used on over 20 missions. It allows custom engine models to be utilized as inputs for computing orbit adjustment maneuvers and spin-axis reorientation maneuvers. Custom engine models were built for each thruster using polynomials to model the performance curves provided by their manufacturer. These models where then used along with the mass specifications of the spacecraft to model each proposed maneuver.

The resulting finite maneuver sequence showed a 10% increase in fuel used (versus the impulsive sequence) from launch to final orbit for the probe that is going the farthest. An increase is expected when changing from impulsive to finite because of the arc loss that occurs, so this 10% increase is within expectations. After the sequence was accurately validated with GMAN, the flight team at UCB was trained on how to use this engine model so that future analysis and operations can be done by them.

PIP Level II: The ST5 Maneuver Planning Tool (Rivers Lamb)

As part of the New Millennium Program, the Space Technology 5 (ST5) mission is designed to prove several new technologies onboard three identical spacecraft. Scheduled to launch in early 2006 onboard a Pegasus launch vehicle, the three spacecraft will achieve at least two distinct formations during the mission's 90-day lifetime.

For the ST5 string-of-pearls formation, along track ΔV requirements for managing the spacecraft separations are very sensitive to slew induced ΔV. Therefore, the formation maneuvers for the three spin-stabilized spacecraft are designed such that there are no attitude slews to change the orientation of the thrust vector with respect to the velocity vector. This maneuver scheme takes advantage of the cyclical relationship between the orbit and attitude geometry to correctly orient the thrust vector.

As a tool designed for mission operations, the ST5 Maneuver Planning Tool uses this slew-free maneuver scheme to search for optimal maneuver opportunities while considering operational constraints. The tool is currently being used to support preliminary maneuver planning for the ST5 mission. In addition, the tool has become a building block for an entire suite of maneuver planning software that will support ST5 mission operations.

(Rivers Lamb has been a full-time Goddard employee since August 2003. Prior to that time, he was a co-op student within the Branch. He received his B.S. degree in Aerospace Engineering from Virginia Tech.)

PIP Level II: The Maintenance Maneuver Errors Induced by Realistic Actuator and Knowledge Errors in MMS Spacecraft (Dean Tsai)

The Magnetospheric Multi-scale (MMS) Mission utilizes four spinning spacecraft to study the Earth's magnetosphere. The mission requires a regular tetrahedron formation to be maintained with side lengths ranging from 10 km to several thousand kilometers at orbit apogee. In order to reduce the spacecraft complexity and the cost, the current mission concept assumes MMS can achieve its formation goals through open-loop orbit control via ground commands. The open-loop concept, however, requires

maneuvers to be carried with a high level of accuracy, otherwise frequent trimming maneuvers would drive up the high operation cost.

The PIP II project is an extension of the PIP I project titled “The Effects of Attitude Maneuvers on the MMS Formation,” which effectively supported the argument of eliminating attitude slew maneuvers during the entire mission phases due to fuel budget constraints. Instead, an alternative maneuver concept, which enables the spinning spacecraft to move freely in space without attitude slew, was suggested. The PIP II project also enhanced the thruster model of the rigid body simulation that was previously developed. The enhanced simulation was used to quantify the effects of realistic errors on formation maintenance maneuver accuracy. Several realistic errors and uncertainties including thrust magnitude and direction uncertainties, attitude and spin-phase knowledge, unknown nutation angles, and center-of-gravity uncertainties are considered.

The results of the PIP II analyses suggested the realistic errors have small, but noticeable, impacts on the orbit maneuvers accuracy. More alarmingly, the results suggested that some of the more stringent formation flying requirements could be violated because of these system errors. The MMS flight dynamics team is now in the process of understanding the formation flying requirements, and at the same time, formulating methods for reducing maneuver errors.

(Dean Tsai started at Goddard in February, 2004. He received his B.S. degree in Mechanical Engineering from the University of California. He is currently pursuing a M.S. degree in Electrical Engineering from the Johns Hopkins University.)

6.3 COOPERATIVE EDUCATION PROGRAM

The Cooperative Education Program integrates academic study with full time meaningful professional experience. This allows the students, through study and work experience, to enhance their academic knowledge, personal development, and professional preparation.

Edwin Dove entered the coop program at the start of his senior year at the Pennsylvania State University, where he was pursuing a B.S. degree in Aerospace Engineering. In order to gain experience in the two groups within FDAB, Edwin was placed in the Attitude and Orbit groups for 6-month intervals. While in the Orbit group, Edwin's mentor was Mark Woodard. Edwin’s main project for the Orbit group was to create a comparative analysis between several orbital lifetime prediction programs, such as STK/Lifetime and GTDS. The purpose of the analysis was to find a possible replacement for PC-Lifetime, one of the FDABs analytical lifetime prediction programs. Edwin also presented the results of the analysis and recommended improvements to STK/Lifetime at the 2004 STK Users Conference in Chantilly, Virginia. While in the Attitude group, Edwin's mentor was Paul Mason. Edwin generated a summary of the thruster modes (Delta V and H) for SDO, updated Solar Dynamics Observatory (SDO) Simulink thruster models, updated duty cycle analysis for SDO, and learned stability analysis related to SDO. During Edwin's co-op work, he was involved in the New Employee Welcoming Board (NEWB), created the Goddard 101 Handbook for NEWB, and provided input for several of NEWB's events.

Stephanie Gil is a senior majoring in mechanical/aerospace engineering at Cornell University. She completed her second rotation at NASA Goddard over the past summer from July to August 2005. During this time, Stephanie expanded on her previous work for the solar sail team at Goddard. Her two major focuses of work for the solar sail team included simulation of solar sail dynamics using STK and a full analysis of the effects of solar sail surface deformations on induced thrusts and torques. She had challenged and revised the simulation capabilities of STK, which was unable to accurately model the unique coupling effects of sail attitude and thrust. During the last fiscal year (FY04), Stephanie worked

on a simplified model to analyze the effects of sail surface deformations in two dimensions. During her most recent rotation, Stephanie expanded this model to be a three-dimensional, higher fidelity model, and once again analyzed the results. She created two Matlab tools, one to model the three- dimensional surface containing billows, material sag, and boom droop, and a second tool to read in the surface data in matrix form and perform the necessary calculations to determine induced forces and torques about the sail center. This has assisted in gaining a better understanding of solar sail behavior as a function of degrees of deformation on the sail surface and Sun incidence angle. This information will be useful in designing appropriate attitude control algorithms for the sail. She has documented all of her work in the form of reports and user manuals and had also given a presentation of her results to the solar sail team and to the Guidance and Navigation Control branch in February.

Mika Robertson started her first cooperative education co-op rotation in May 2005, and is the George Washington University's first co-op student in the FDAB. Her rotation is an ongoing term, participating on a part-time basis during the school year and full time in the summer term.

Mika's position is in the Flight Dynamics Facility, working as an assistant to the FDF Operations Director. She is involved in ongoing support of spacecraft operations through the MOMS Orbit Task as Task Monitor, and participates in planning of mission support in the FDF. She is also involved in the Branch strategic implementation planning as the facilitator and member of the planning group representing operations. Mika is also the lead planner for the FDF Emergency Operations plan development.

Mika is currently a full-time student at GWU, and has been admitted to candidacy for her Doctor of Science degree. She will continue her full time studies next semester focusing on research, and will continue her work with the FDF and FDAB.

Neal Patel is a junior in aerospace engineering at the Georgia Institute of Technology. Neal's first co-op rotation began in May 2005 and ended in August 2005. During his time at NASA Goddard, Neal worked with the attitude group on the Lunar Reconnaissance Orbiter (LRO) project. Neal began his term by learning the basics behind attitude control, and the necessary mathematics required to make a high fidelity model for the project. By manipulating older models and creating new models, he was able to create a simulation that accurately represented the LRO. During his next co-op term, Neal will continue updating the models, and run tests using this simulation to help the attitude team assess the orbiter.

6.4 NEW EMPLOYEE WELCOMING BOARD (NEWB)

In December 2003, the NEWB was developed in Code 500 to improve the transition for new employees into the workforce at Goddard. Since NEWB’s inception, many Code 595 employees have been actively involved in this now Centerwide organization.

NEWB members have created a Goddard 101 Handbook full of useful information for any Goddard employee, as well as developed a supervisory checklist to assist management in acclimating the new employees. The NEWB organization has also created a Buddy Program designed to help orient the new employee and ease the transition of the first two weeks of employment.

Code 595 employees have helped plan new employee events, participated in the Buddy Program, and also helped developed the NEWB organization itself.

[Technical contact: Leigh Janes]

6.5 SYSTEMS ENGINEERING EDUCATION DEVELOPMENT (SEED) PROGRAM

http://seacd.gsfc.nasa.gov/SEED/

The SEED Program is designed to develop systems engineers for the NASA GSFC environment from incumbent mid-level, (GS-13) professionals. The SEED Program is based on four fundamental elements: mentoring by senior systems engineers, a curriculum of courses, on-the-job training through rotational assignments, and applied human systems leadership training. The SEED program is designed to have mentees complete their tenure in two to three years. During the program, the participants are exposed to many areas of systems engineering through educational courses and task assignments to active NASA mission projects. They also participate in leadership and technical workshops. Graduates receive noncompetitive consideration for a senior level (GS-14) systems engineering position.

The SEED Program is managed by The Mission Engineering and Systems Analysis Division (MESAD) of the Applied Engineering and Advanced Technology Directorate (AETD) of Goddard. SEED participants are detailed to Code 592 (Systems Engineering Services and Advanced Concepts Branch) for the duration of the program.

The FDAB served as a rotational assignment for one of the SEED mentees, Lilly Brashers, for three months this year. She learned about GNC attitude analysis and trajectory analysis. In addition, the FDAB sent one of its members into the SEED world. Steve Andrews began the program during FY04. During that time, he participated in numerous training classes for technical and personal development. His first rotational assignment was with the Optics Branch (Code 551) for six months. His second assignment has been as a Spacecraft Systems Engineer on the LRO. At the end of each assignment, a debriefing presentation must be made to the SEED advisory board.

The FDAB provides a good background for engineers who want to try systems engineering, and also provides a great opportunity for rotational assignments for SEED participants.

[Technical contact: Stephen Andrews]

7.0 OUTREACH ACTIVITIES

7.1 TABLESAT

TableSat is an interactive, single-axis spacecraft simulator designed as a tool for demonstrating and teaching the process and challenges of designing attitude control systems. It is composed of a 15" diameter disc balanced on a center spindle; four coarse Sun sensors, a three-axis magnetometer, and a single-axis gyro for sensors; two 12 V computer fans for actuators; wireless Ethernet for communications; a battery pack for power; and an onboard flight processor. The table was originally developed as a demonstration tool for the "Attitude Control Systems for Non-ACS Engineers" course. After receiving positive feedback from class participants, TableSat was cleaned-up and expanded. It has been used as a demonstration tool in undergraduate linear controls classes, bridging the gap between theoretical explanations and actual applications of controller design. It has also been used to demonstrate the fundamentals of control systems to middle- and high school students and teachers.

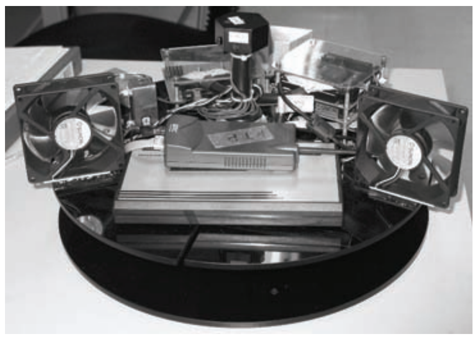

Figure 7-1. TableSat

Over this past year, with help from the University of Maryland, TableSat was upgraded such that it can serve as a better demonstration tool for undergraduate students in linear controls classes. TableSat now has a new, faster, flight processor with more memory; larger fans; a more powerful battery; and a new communications system. As a result of the new flight processor, the TableSat flight code has been rewritten to include more functionality, including variable control, estimation, and actuation rates; onboard state estimation; the ability to implement continuous, "bang-bang,", or pulse width modulation actuation; and onboard friction compensation to allow TableSat to be treated as an ideal system. Two different Simulink block diagrams can be used to control the new TableSat, allowing the user to test controllers and state estimators using a Simulink block diagram, or load controllers and state estimators directly to the flight processor. In addition, a Matlab Graphical User Interface (GUI) has been developed to allow users to easily vary the different TableSat parameters.

As part of the redesign effort, a system model of TableSat was also created. Development of the system model included development of the TableSat equations of motion and identification of the TableSat moment of inertia, TableSat friction, fan friction, and as well as several additional parameters. The system model was turned into a Matlab/Simulink based model that can be used to help design and test controllers and state estimators. The model was verified by comparing predicted model data against actual TableSat data. The model has also been used to successfully design several different linear controllers and state estimators, including a simple Proportional Derivative (PD) controller, and a model-based controller/observer.

[Technical contact: Missie Vess]

7.2 FLIGHT MECHANICS SYMPOSIUM

The Flight Mechanics Symposium took place October 18–20, 2005 in the Building 3 auditorium. The symposium provides an opportunity for specialists in spacecraft flight dynamics to present, discuss, and exchange information on a wide variety of topics. Fifty technical papers are scheduled to be presented over the three days of the symposium. The session topics include navigation, guidance, and optimization; attitude and rate estimation; formation flying design and simulation; orbit estimation, propagation, and modeling; attitude control and dynamics; and calibration, error modeling, and fault detection. Papers will be published in a formal NASA Conference Publication (NASA CP).

[Technical contact: Julie Thienel]

7.3 UNIVERSITY OF MARYLAND ENAE-691 SATELLITE DESIGN COURSE

Two senior members of the Flight Dynamics Analysis Branch assisted in teaching the graduate-level course in Satellite Design (ENAE-691) during the University of Maryland Spring 2005 semester. The course was coordinated by GSFC retiree John Hrastar and Mission Systems Engineering Branch member Jim Andary and was taught by a number of GSFC employees and other guest lecturers. Dave Folta delivered the lecture on orbital dynamics and Jim O'Donnell covered attitude control. In addition to lecturing the class, both Dave and Jim participated in evaluating the class's satellite design group project presentations and reports.

[Technical contact: James O’Donnell]

8.0 INTERAGENCY ACTIVITIES

8.1 NASA TECHNICAL STANDARDS PROGRAM

http://www.ccsds.org/
http://standards.gsfc.nasa.gov/

The FDAB supports the NASA Technical Standards Program by contributing to the work of the GSFC standards program, the NASA Data Standards Working Group (NDSWG), and the Consultative Committee for Space Data Systems (CCSDS). The GSFC standards program aims to expand the scope of best practices, and to develop an Agency-endorsed database of preferred technical standards for NASA. The NDSWG is the hub of the NASA Data Standards Program and is sponsored by the NASA Data Standards Program Office (NDSPO).

The Consultative Committee for Space Data Systems (CCSDS) is an international organization of space agencies interested in mutually developing standard data handling techniques, to reduce cost, risk, and development time, and to promote enhanced interoperability and cross-support.

Summary of accomplishments by the CCSDS navigation working group (WG):
In FY05, the CCSDS navigation workshops were hosted by the *Centre National d'Etudes Spatiales* (CNES), Toulouse, France, November 2004; the European Space Agency (ESA) in a joint effort with the Object Management Group (OMG), Athens, Greece, April 2005; and NASA in a joint effort with OMG, Atlanta, GA., September 2005.

Fall 2004 workshop accomplishments: Discussed action items. Conducted a detailed review of all Navigation WG documentation, in development, a Green Book (GB); an Extensible Mark-up Language (XML) specification white book, which describes schemas for all navigation data messages; a Tracking Data Message (TDM) white book; and an Attitude Data Messages (ADM) white book. Assessed future activity schedule, considering possible requirements for future standards to support spacecraft-to-spacecraft navigation data exchanges.

Supported the Mission Operations and Information Management Services (MOIMS) Plenary meeting and presented the WG report.

Spring 2005 workshop accomplishments: Discussed action items. Discussed topics pertaining to interface with other working groups or external efforts; such as Delta Differential One-way Range (delta-DOR), Cross Support Services (CSS) data transfer services, XML Telemetric and Command Exchange (XTCE) document, and ISO SC14 collision avoidance. Then had conversations with personnel of the CSS data transfer services WG, the Ranging WG and the OMG Space Data Task Force (SDTF), pertaining to those topics. Conducted detailed discussions and review of the ADM, the TDM, and the XML specification white books; including all related material for the Navigation GB. A question from the Interagency Operations Advisory Group (IOAG) pertaining to Delta Differential One-way Range (delta-DOR) was resolved based on material included in the Navigation WG TDM and GB, as well as the Ranging WG Blue Book.

Supported the MOIMS Area Plenary meeting and presented the WG report.

September 2005 workshop accomplishments: Completed all necessary material in the ADM, TDM, and XML white books to achieve promotion to red book status; to be released for CCSDS wide review, along with an updated version of the green book, which provides supporting technical information.

Minutes of the CCSDS series workshops, an official standard for orbit data messages (ODM) and all other navigation WG documents are available on line, at the CCSDS Web site.

[Technical contact: Felipe Flores-Amaya]

8.2 GLOBAL POSITIONING SYSTEM (GPS) MODERNIZATION

In recognition of GSFC's role as a leader in the area of space based applications of GPSs, the branch provided support or expertise to a number of external agencies related to ongoing GPS activities. In September 2005, the first modernized GPS satellite, capable of broadcasting the new, second civilian "L2C" signal, was launched. NASA was appointed the technical lead for "L2C Transition," and the branch worked with other civil agencies such as the Department of Transportation, USGS, and the U.S. Air Force (USAF) to coordinate the plan for how this signal would be used by NASA and other stakeholders following launch, but prior to the signal reaching official full operational capability in the next decade. The branch was also involved with coordinating JPL participation in the on-orbit testing of the L2C signal, and the introduction of L2C capable GPS receivers into the Global network that is maintained by JPL.

The USAF is currently in the process of procuring the next series of GPS satellites to begin launching in 2013. The GPS III program, as it is known, will provide the next generation of positioning, navigation, and timing (PNT) capabilities, including improvements in accuracy, availability and integrity as well as increased anti-jam performance to meet the future needs of civil and military users. GPS III will also introduce a modernized civil signal on the L1 carrier, called L1C. The branch has supported the GPS III Phase A program, through participation in major reviews and technical interchange meetings with the two prime contractors. The branch has also supported the USAF in the preparation for the Request for Proposal (RFP) for GPS III which will be released at the end of 2005.

In addition, an interagency team consisting of space users of GPS from NASA and the Department of Defense (DoD) have been engaged with the USAF since 2003 with the objective of improving GPS performance (availability, received power) for high altitude space users (above 3000 km). In recent years, the utility of GPS-based navigation has been demonstrated for users extending to the geostationary altitude, and in some cases higher. These users must, however, cope with significantly reduced received power levels and sparse signal availability. Additionally, there has been a perceived risk associated with utilizing these signals in critical applications because there are no specific requirements governing GPS signals transmitted beyond the limb of the Earth. The branch has led the technical analysis for this team, and has coordinated the efforts to participate in the Air Force's formal requirements process and improve the existing space user requirements for GPS III. This effort has resulted in two main achievements: First, formal "threshold" requirements have been incorporated into the GPS III system Capability Development Document (CDD) for the power and availability of GPS signals transmitted beyond the limb of the Earth and utilized by space users. Requirements for availability and signal strength were allocated to three service volumes:

- Terrestrial service volume—3000 km and below
- Medium orbit service volume—3000–8000 km altitude
- High orbit service volume—8000–36500 km altitude

These threshold requirements guarantee that GPS III will provide backwards compatibility with the signals available at these altitudes from the current GPS constellation (although there is no current specification on the signals transmitted today). Second, the USAF made a commitment, to engage in a

trade study as part of the GPS III phase B program (starting mid 2006) to investigate changes that could be made to improve performance for future space users, towards meeting the objective requirements of increased received power and improved availability for high altitude space users. The NASA/DoD team has been working to compile analyses that will be used to guide this trade study in 2006, which will be documented in a formal report.

[Technical contact: Mike Moreau]

8.3 NASA ENGINEERING AND SAFETY CENTER (NESC) SUPPORT

http://nesc.nasa.gov

NESC was formed in the wake of the Space Shuttle *Columbia* accident to serve as an independent technical resource for NASA managers and employees. The objective of the NESC is to improve safety by performing in-depth independent engineering assessments, testing, and analysis to uncover technical vulnerabilities and to determine appropriate preventative and corrective actions for problems, trends, or issues within NASA's programs, projects, and institutions.

Several FDAB members have provided support to the NESC this year through their participation in activities of the Guidance, Navigation and Control (GNC) Super-Problem Resolution Team (SPRT). Russell Carpenter supported the DART MIB (details are available elsewhere in this publication). David Mangus provided GN&C perspective at NESC-supported reviews during the lead-up to the Huygens Probe deployment. Along with other members of MESA Division staff, some FDAB members participated at the 2005 GN&C SPRT face-to-face meetings at Kennedy Space Center (April) and San Francisco/Ames Research Center (August). Facility tours at both locations have broadened the exposure of FDAB staff to the GN&C work happening throughout NASA. FDAB Associate Branch Head Jim O'Donnell attended the August meeting to present information about the ST7 mission.

FDAB analysts also participated in Return To Flight activities through their support of the NESC. Early in FY05, Julie Thienel completed her work on the Shuttle Recurring Anomaly Review, resulting in a final report to NASA Headquarters. This summer, David Mangus, Peiman Maghami, and Scott Starin supported the NESC review of the Orbiter Repair Maneuver (ORM). The ORM is a contingency plan in which tile damage unreachable while docked to the Space Station would be reached by undocking and repositioning the Orbiter using the Orbiter's robotic arm.

David Mangus serves as a Core GN&C SPRT representative, and several Branch members serve as GN&C SPRT Technical Experts. Oscar Hsu, Scott Starin, and John Van Eepoel have continued their service as the GN&C SPRT Technical Support staff.

[Technical contact: Scott Starin]

8.4 LOW-THRUST WORKING GROUP

GSFC continued its participation this year in the interagency Low Thrust Working Group. The working group, funded by NASA HQ and managed by MSFC, is developing a new state-of-the-art suite of low-thrust tools. The tools being developed fulfill different niches and are designed to be compatible with each other. The tools, Mission Analysis Low Thrust Optimization (MALTO), Mystic, Optimal Trajectory by Implicit Simulation (OTIS), Simulated N-body Analysis Program (SNAP), and Copernicus, are needed

to meet the needs of our internal and external customers who are planning ever more complex missions requiring low thrust propulsion.

GSFC has been particularly involved in the use of one of these tools, Copernicus, which is being developed by Dr. Cesar Ocampo of the University of Texas at Austin. Copernicus is a tool which uses optimal (indirect), suboptimal (direct), and hybrid optimization methods to design missions that use virtually any type of propulsion system either impulsive or continuous. GSFC plans to use Copernicus to support the development of lunar architecture concepts. In particular, Copernicus can be used to optimize lunar descent and ascent trajectories. Dr. Ocampo recently taught a very well received two-day course at GSFC reviewing the trajectory design concepts that Copernicus uses. The FDAB plans to participate in further training in January 2006 when Dr. Ocampo leads a seminar on the use of Copernicus to design complex missions at a Systems Analysis Workshop sponsored by the In-Space Propulsion (ISP) Technology Office at MSFC.

Copernicus and SNAP are scheduled to be widely released to both academia and industry, to the maximum extent possible, in October 2005. Thus far, the working group has held three Technical Interchange Meetings (TIMs). The next Low Thrust TIM will be held March 27–30, 2006 at MSFC.

[Technical contact: Steven Cooley]

8.5 SPACE COMMUNICATIONS ARCHITECTURE WORKING GROUP (SCAWG)

FDAB personnel contributed significantly to two reports by the SCAWG Navigation subteam: "Lunar Navigation Systems Alternatives for Continuous Full Surface Coverage," and "NASA Mission Impact Analysis of the Use in Space of Future GPS Constellation Options." The former compared the navigation utility of a variety of lunar communications and navigation constellations, and the latter evaluated a proposal to change the current 6-plane GPS constellation to a 3-plane constellation.

[Technical contact: Russell Carpenter]

8.6 DART MISHAP INVESTIGATION BOARD (MIB)

On April 15, 2005, the Demonstration of Autonomous Rendezvous Technology (DART) spacecraft was successfully deployed from a Pegasus XL rocket launched from the Western Test Range at Vandenberg Air Force Base. DART was designed to autonomously rendezvous with, and perform a variety of maneuvers in close proximity to, the Multiple Paths, Beyond-Line-of-Sight Communications (MUBLCOM) satellite, launched in 1999. DART performed nominally during the first eight hours through the launch and early orbit phase and through the rendezvous phase of the mission, accomplishing all objectives up to that time, even though ground operations personnel had noticed anomalies with the navigation system. During proximity operations, the spacecraft began using much more propellant than expected. Approximately 11 hours into the mission, DART detected that its propellant supply was depleted and, therefore, began a series of maneuvers for departure and retirement of the spacecraft. Although it was not known at the time, DART had actually collided with MUBLCOM 3 mi and 49 s before initiating retirement.

Because DART failed to achieve its main mission objectives, a Type A Mishap was declared. None of the 14 requirements related to the proximity operations phase, which were the critical technology objectives, were met. It should be noted, however, that the Pegasus portions of the DART mission, including the launch and early orbit phase, rendezvous, and departure and retirement, were completely successful.

FDAB personnel supported the work of the MIB, as Deputy Chairman, and also in supporting analysis roles; A.I. Solutions personnel assisted with some of this analysis work. Based on hardware testing, telemetry data analysis, and numerous simulation runs, the board developed an explanation of the mishaps and their underlying causes. Two separate events and causal factors timelines were developed, one for DART's premature retirement and another for DART's collision with MUBLCOM. Events and causal factors diagrams were developed: resulting in the identification of 15 root causes for the mishaps.

[Technical contact: Russell Carpenter]

APPENDIX A: CONFERENCE PAPER ABSTRACTS

Given below are abstracts from professional papers and technical presentations that were prepared and delivered in FY05 by branch members.

CONFERENCES

2004 International Symposium on Space Flight Dynamics, in Munich, Germany, October 2004

"Control of the Laser Interferometer Space Antenna," by P. G. Maghami, T. T. Hyde, and J. Kim

ABSTRACT: The Laser Interferometer Space Antenna mission is a planned gravitational wave detector consisting of three spacecraft in heliocentric orbit. Laser interferometry is used to measure distance fluctuations between test masses aboard each spacecraft to the picometer level over a 5 million kilometer separation. The Disturbance Reduction System comprises the pointing and positioning control of the spacecraft, electrostatic suspension control of the test masses, and point-ahead and acquisition control. This paper presents a control architecture and design for the Disturbance Reduction System to meet the stringent pointing and positioning requirements. Simulations are performed to demonstrate the feasibility of the proposed architecture.

"Hardware in the Loop Testing of Continuous Control Algorithms for a Precision Formation Flying Demonstration Mission," Bo Naasz, Richard Burns, David Gaylor, and John Higginbotham

ABSTRACT: Precision Formation Flying (PFF) refers to the class of distributed spacecraft missions that require precise, continuous control of the relative motion of multiple spacecraft, implemented through inter-satellite crosslinks. PFF technology will enable advanced science missions by using spacecraft Guidance, Navigation, and Control (GNC) systems to place distributed optics and detectors at distances not feasible on traditional spacecraft. Examples of potential PFF missions include Terrestrial Planet Finder, MicroArcsecond Imaging Mission, and Stellar Imager. While these missions will most likely occur in orbits near libration points, or in deep space, preliminary on-orbit demonstration of PFF technology is likely to occur in Low Earth Orbit (LEO) (for example in the proposed PFF version of New Millennium Program's Space Technology 9 mission).

Demonstration of PFF in LEO requires a unique combination of formation flying guidance and control strategies. These strategies must consider the relatively large differential gravitational and atmospheric effects present in LEO, while providing a test environment relevant to more distant orbital regimes. To this end, these strategies must include the use of naturally stable formations for staging and parking, as well as brief experimental periods with formations defined by slight deviations from natural motion so that continuous control is required but not prohibitively expensive.

In this paper, a sample LEO PFF demonstration mission sequence is proposed which includes 8 hour sequences of continuous control application separated by periods of loose formation keeping. Various GNC strategies are considered for use in the PFF experiment phases, and implemented and tested in a realistic Hardware-in-the-Loop (HWIL) simulation.

"Relative Navigation Strategies For The Magnetospheric Multiscale Mission," Cheryl Gramling, Russell Carpenter, Taesul Lee, and Anne Long

ABSTRACT: This paper evaluates several navigation approaches for the Magnetospheric Multiscale (MMS) mission, which consists of a tetrahedral formation of satellites flying in highly eccentric Earth orbits. For this investigation, inter-satellite separations of approximately 10 kilometers near apogee are used for the first two phases of the MMS mission. Navigation approaches were studied using ground station two-way Doppler measurements, Global Positioning System (GPS) pseudorange measurements, and cross-link range measurements between the members of the formation. An absolute position accuracy of 15 kilometers or better can be achieved with most of the approaches studied, and a relative position accuracy of 100 meters or better can be achieved at apogee in several cases.

Institute of Navigation National Technical Meeting, San Diego, CA, January 24–26, 2005.

"Hardware in-the-Loop Demonstration of Real-Time Orbit Determination in High Earth Orbits," Mike Moreau, Bo Naasz, Jesse Leitner, Russell Carpenter, and Dave Gaylor

ABSTRACT: This paper presents results from a study conducted at Goddard Space Flight Center (GSFC) to assess the real-time orbit determination accuracy of GPS-based navigation in a number of different high Earth orbital regimes. Measurements collected from a GPS receiver (connected to a GPS radio frequency (RF) signal simulator) were processed in a navigation filter in real-time, and resulting errors in the estimated states were assessed. For the most challenging orbit simulated, a 12 hour Molniya orbit with an apogee of approximately 39,000 km, mean total position and velocity errors were approximately 7 meters and 3 mm/s respectively. The study also makes direct comparisons between the results from the above hardware in-the-loop tests and results obtained by processing GPS measurements generated from software simulations. Care was taken to use the same models and assumptions in the generation of both the real-time and software simulated measurements, in order that the real-time data could be used to help validate the assumptions and models used in the software simulations. The study makes use of the unique capabilities of the Formation Flying Test Bed at GSFC, which provides a capability to interface with different GPS receivers and to produce real-time, filtered orbit solutions even when less than four satellites are visible. The result is a powerful tool for assessing onboard navigation performance in a wide range of orbital regimes, and a test-bed for developing software and procedures for use in real spacecraft applications.

15th AAS/AIAA Space Flight Mechanics Conference, Copper Mountain, Colorado, January 23–27, 2005

"A Direct Method for Fuel Optimal Maneuvers of Distributed Spacecraft in Multiple Flight Regimes," AAS 05-158, Steven P. Hughes, D. S. Cooley, and Jose J. Guzman

ABSTRACT: We present a method to solve the impulsive minimum fuel maneuver problem for a distributed set of spacecraft. We develop the method assuming a non-linear dynamics model and parameterize the problem to allow the method to be applicable to multiple flight regimes including low-Earth orbits, highly-elliptic orbits (HEO), Lagrange point orbits, and interplanetary trajectories. Furthermore, the approach is not limited by the inter-spacecraft separation distances and is applicable to both small formations as well as large constellations. Semianalytical derivatives are derived for the changes in the total Delta-V with respect to changes in the independent variables. We also apply a set of

constraints to ensure that the fuel expenditure is equalized over the spacecraft in formation. We conclude with several examples and present optimal maneuver sequences for both a HEO and libration point formation.

AAS/AIAA Space Flight Mechanics Meeting, Lake Tahoe, CA, August 7–11, 2005

"Mission Design of the First Robotic Lunar Exploration Program Mission: The Lunar Reconnaissance Orbiter," M. Beckman and D. Folta

ABSTRACT: The Lunar Reconnaissance Orbiter (LRO) is the first of the Robotic Lunar Exploration Program's (RLEP) missions to the moon. LRO is a one-year mission to be flown in a low (50 km) polar lunar orbit. It will be launched on a Delta II class launch vehicle in late 2008 onto a short coast minimum energy transfer, with the proper lighting conditions, and with a launch window of about six days per month. During the nominal mission, orbit determination is required to be accurate to 500 m in total position and 18 m radially, but is expected to be a factor of two to three better. The two-month commissioning orbit, and possibly the extended mission, will be in a lunar frozen orbit at 30 x 216 km altitude, which minimizes stationkeeping fuel costs.

"Finding Acceptable James Webb Space Telescope Mission Orbits From a Fixed Ariane Flight Profile," M. Beckman and L. Janes

ABSTRACT: The James Webb Space Telescope (JWST) will be launched into orbit about the Sun/Earth L2 libration point. Trajectory design was recently completed which included expected separation states from the Ariane launch vehicle, constraints such as eclipses, maximum orbit size, maximum Sun-Vehicle-Earth/Moon angles, and launch opportunities. The results of the trajectory design give a set of possible trajectories for JWST with bounded stray light zones and provide a complete launch window. This data is also used to design the initial trajectory correction maneuver such that a maneuver towards the Sun is not required.

"Enabling Exploration Missions Now: Applications of On-Orbit Staging," David C. Folta, Frank J.Vaughn, Jr., Paul A. Westmeyer, Gary S. Rawitscher, and Francesco Bordi

ABSTRACT: Future NASA exploration objectives are difficult to meet using current propulsion architectures and fuel-optimal trajectories. We introduce the concept of On-Orbit Staging and combine it with the idea of pre-positioned fuel and supply depots to increase payload mass and reduce overall cost, schedule, and risk for missions proposed as a part of the NASA Vision for Space Exploration. The On-Orbit Staging concept extends the implementation of ideas originally put forth by Tsiolkovsky, Oberth and Von Braun to address the total mission design. Applying the basic staging concept to all major propulsive (orbit) events and utilizing technological advances in propulsion efficiency and architecture allows us to demonstrate that exploration and science goals can be met more effectively and efficiently. As part of this architecture, we assume the readiness of automated rendezvous, docking/berthing, and assembly technology, all of which will be required for any credible exploration architecture. Primary cost drivers are identified and strategies that utilize On-Orbit Staging to reduce these costs are discussed.

"Eos Aura Ascent Planning—Establishing The Earth Science Afternoon Constellation," Richard J. McIntosh and Lauri K. Newman
AAS 05-363

ABSTRACT: This paper describes the trajectory planning and operations efforts of the NASA Goddard Space Flight Center Flight Dynamics team to place the Earth Observing System (EOS) Aura spacecraft in its mission orbit to form the fundamental beginnings of the Earth Science Afternoon Constellation. Aura is required to fly in a particular location relative to the World Reference System –2 (WRS-2) path of EOS Aqua. Pre-mission analysis is discussed, including choice of launch window start and duration to meet constellation requirements, nominal ascent scenarios, and contingency plans. Actual as-flown orbit-raising maneuvers are also documented, including operational maneuver constraints, maneuver calibration results, conjunction assessments for collision avoidance, and backup burn options.

"Inclination Adjust Maneuver Planning and Execution For The Earth Science Afternoon Constellation," David K. Rand, Lauri K. Newman, and Kevin T. Work
AAS 05-364

ABSTRACT: Following a series of orbit-raising maneuvers, Earth Observing System (EOS) Aura joined its sister spacecraft, EOS Aqua, in their desired mission orbits on August 9, 2004 to form the beginning of the Earth Science Afternoon Constellation. Member missions of this Constellation are independently funded and operated by their responsible organizations; however, each controls its orbit to remain within a pre-designated control box to ensure safety for the other members. While this control box philosophy works for in-plane orbit control, it does not account for plane change maneuvers. If one mission performs a plane change, the rest are forced to follow suit or break the Constellation. Prior to Aura launch, the Aqua Project had agreed with some Constellation members to perform a set of required inclination adjust maneuvers prior to April 2005. Since Aura was then on orbit, it had to perform matching maneuvers to remain in the Constellation. This paper details the planning that was performed to execute the combined inclination maneuvers, including leveraging Aqua lessons learned, examining various maneuver date options in concert with Aura ascent planning, contingency planning, and collaboration between the Flight Operations Teams to ensure that the maneuvers could be executed from the shared control center by shared personnel without issue. In addition, the actual maneuver results are documented along with lessons learned. Some discussion of performing inclination maneuvers in the future with more than two Constellation members is also provided.

"Analysis for Monitoring the Earth Science Afternoon Constellation," Peter Demarest, Karen V. Richon, and Frank Wright
AAS 05-368

ABSTRACT: The Earth Science Afternoon Constellation consists of Aqua, Aura, PARASOL, CALIPSO, CloudSat, and OCO. The coordination of flight dynamics activities between these missions is critical to the safety and success of the Afternoon Constellation. This coordination is based on two main concepts, the control box and the zone-of-exclusion. This paper describes how these two concepts are implemented in the Constellation Coordination System (CCS). The CCS is a collection of tools that enables the collection and distribution of flight dynamics products among the missions, allows cross-mission analyses to be performed through a web-based interface, performs automated analyses to monitor the overall constellation, and notifies the missions of changes in the status of the other missions.

"An Overview of the Earth Science Afternoon Constellation Contingency Procedures," Karen V. Richon and Warren Case
AAS 05-369

ABSTRACT: The Earth Science Afternoon Constellation comprises NASA missions Aqua, Aura, CloudSat and OCO, the joint NASA/CNES mission CALIPSO and the CNES mission PARASOL. Both NASA and CNES offices are responsible for ensuring that contingency plans or other arrangements exist to cope with contingencies within their respective jurisdictions until the conclusion of all Afternoon Constellation operations. The Mission Operations Working Group, comprised of members from each of the missions, has developed the high-level procedures for maintaining the safety of this constellation. Each contingency situation requires detailed analyses before any decisions are made. This paper describes these procedures, and includes defining what constitutes a contingency situation, the pertinent parameters involved in the contingency analysis and guidelines for the actions required, based on the results of the contingency analyses.

"Enabling Exploration Missions Now: Applications of On-Orbit Staging," David C. Folta, Frank J. Vaughn, Jr., Paul A. Westmeyer, Gary S. Rawitscher, and Francesco Bordi

ABSTRACT: Future NASA exploration objectives are difficult to meet using current propulsion architectures and fuel-optimal trajectories. We introduce the concept of On-Orbit Staging and combine it with the idea of pre-positioned fuel and supply depots to increase payload mass and reduce overall cost, schedule, and risk for missions proposed as a part of the NASA Vision for Space Exploration. The On-Orbit Staging concept extends the implementation of ideas originally put forth by Tsiolkovsky, Oberth and Von Braun to address the total mission design. Applying the basic staging concept to all major propulsive (orbit) events and utilizing technological advances in propulsion efficiency and architecture allows us to demonstrate that exploration and science goals can be met more effectively and efficiently. As part of this architecture, we assume the readiness of automated rendezvous, docking/berthing, and assembly technology, all of which will be required for any credible exploration architecture. Primary cost drivers are identified and strategies that utilize On-Orbit Staging to reduce these costs are discussed.

AIAA Guidance, Navigation, and Control Conference, San Francisco, CA, August 15–18, 2005

"Hubble Space Telescope Angular Velocity Estimation During the Robotic Servicing Mission," Julie Thienel, John Van Eepoel, Steve Queen, and Rob Sanner

ABSTRACT: In 2004 NASA began investigation of a robotic servicing mission for the Hubble Space Telescope (HST). Such a mission would require estimates of the HST attitude and rates in order to achieve a capture by the proposed Hubble robotic vehicle (HRV). HRV was to be equipped with vision-based sensors, capable of estimating the relative attitude between HST and HRV. The inertial HST attitude is derived from the measured relative attitude and the HRV computed inertial attitude. However, the relative rate between HST and HRV cannot be measured directly. Therefore, the HST rate with respect to inertial space is not known. Two approaches are developed to estimate the HST rates. Both methods utilize the measured relative attitude and the HRV inertial attitude and rates. First, a nonlinear estimator is developed. The nonlinear approach estimates the HST rate through an estimation of the inertial angular momentum. Second, a linearized approach is developed. The linearized approach is a pseudo-linear Kalman filter. Simulation test results for both methods are given. Even though the development began as an application for the HST robotic servicing mission, the methods presented are applicable to any rendezvous/capture mission involving a non-cooperative target spacecraft.

SPIE Optics & Photonics 2005 Symposium: Optical Modeling and Performance Predictions II, San Diego, CA, July 31–August 4, 2005

“Terrestrial Planet Finder Coronagraph Pointing Control System Design and Evaluation for Flight Baseline 1,” Kuo-Chia Liu, Carl Blaurock, James Alexander, and Larry Dewell

ABSTRACT: The Terrestrial Planet Finder mission will search for Earth-like, extrasolar planets. The Coronagraph architecture option (TPF-C) will use contrast imaging to suppress the bright starlight in order to detect reflected visible light from the planet. To achieve the required contrast ratio stability of 2e-11, the payload pointing stability must be maintained to better than 4 milli-asec (1). The passive TPF-C pointing architecture uses a 3-stage control system combined with a 2-stage passive isolation system to achieve the required pointing accuracy. The active pointing stage includes reaction wheels used for coarse pointing of the spacecraft, a position controlled secondary mirror that provides intermediate alignment, and a Fine Guidance Mirror that provides fine steering control.

Each stage of the Pointing Control System (PCS) introduces some pointing inaccuracy due to actuator non-idealities that cause the physical commands to deviate by some amount from the ideal command, by sensor noises that are fed back through that stage’s actuators to produce physical motions, and by modeling errors that arise because of imprecise knowledge of the dynamics of the system. The PCS must demonstrate the required accuracy of pointing performance in the presence of all of these effects. This paper presents the baseline PCS design and preliminary performance results. These results are compared to the TPF-C error requirements in order to assess the viability of the flight baseline design.

“Passive isolator design for jitter reduction in the Terrestrial Planet Finder Coronagraph,” Carl Blaurock, Kuo-Chia Liu, Larry Dewell, and James Alexander

ABSTRACT: Terrestrial Planet Finder (TPF) is a mission to locate and study extrasolar Earthlike planets. The TPF Coronagraph (TPF-C), planned for launch in the latter half of the next decade, will use a coronagraphic mask and other optics to suppress the light of the nearby star in order to collect visible light from such planets. The required contrast ratio of 5e-11 can only be achieved by maintaining pointing accuracy to 4 milli-arcseconds, and limiting optics jitter to below 5 nm. Numerous mechanical disturbances act to induce jitter. This paper concentrates on passive isolation techniques to minimize the optical degradation introduced by disturbance sources. A passive isolation system, using compliant mounts placed at an energy bottleneck to reduce energy transmission above a certain frequency, is a low risk, flight proven design approach. However, the attenuation is limited, compared to an active system, so the feasibility of the design must be demonstrated by analysis. The paper presents the jitter analysis for the baseline TPF design, using a passive isolation system. The analysis model representing the dynamics of the spacecraft and telescope is described, with emphasis on passive isolator modeling. Pointing and deformation metrics, consistent with the TPF-C error budget, are derived. Jitter prediction methodology and results are presented. Then an analysis of the critical design parameters that drive the TPFC jitter response is performed.

“Precision Telescope Pointing and Spacecraft Vibration Isolation for the Terrestrial Planet Finder Coronagraph,” Larry Dewell, Nelson Pedreiro, Carl Blaurock, Kuo-Chia Liu, James Alexander, and Marie Levine

ABSTRACT: The Terrestrial Planet Finder Coronagraph is a visible-light coronagraph to detect the reflected light from planets that are orbiting within the Habitable Zone of stars, in order to detect and characterize Earth-like planets. The coronagraph instrument must achieve a contrast ratio stability of 2e-

11 in order to achieve its planet detection requirements. This places stringent requirements on several spacecraft subsystems, particularly on the pointing stability and structural vibration of the instrument in the presence of mechanical disturbance: for example, telescope pointing must be accurate to within 4 milli-arcseconds, and the jitter of optics must be less than 5 nm. The purpose of this paper is to communicate the architecture and predicted performance of a precision pointing and vibration isolation approach for TPF-C called Disturbance Free Payload (DFP). In this architecture, the spacecraft and payload fly in close-proximity, and interact with forces and torques through a set of non-contact interface sensors and actuators. In contrast to other active vibration isolation approaches, this architecture allows for isolation down to zero frequency, and the performance of the isolation system is not limited by sensor characteristics. This paper describes the DFP architecture, interface hardware and technical maturity of the technology. In addition, an integrated model of TPF-C Flight Baseline 1 (FB1) is described that allows for explicit computation of performance metrics from system disturbance sources. Using this model, it is shown that the DFP pointing and isolation architecture meets all pointing and jitter stability requirements with substantial margin. This performance relative to requirements is presented, and several fruitful avenues for utilizing performance margin for system design simplification are identified.

AIAA Infotech@Aerospace, Arlington, VA, September 26–29, 2005

"A Demonstration of a Retrofit Architecture for Intelligent Control and Diagnostics of a Turbofan Engine," Jonathan S. Litt, James A. Turso, Neerav Shah, T. Shane Sowers, and A. Karl Owen

ABSTRACT: A retrofit architecture for intelligent turbofan engine control and diagnostics that changes the fan speed command to maintain thrust is proposed and its demonstration in a piloted flight simulator is described. The objective of the implementation is to increase the level of autonomy of the propulsion system, thereby reducing pilot workload in the presence of engine degradation due to wear, and anomalies. The main functions of the architecture are to diagnose the cause of changes in the engine's operation, warning the pilot if necessary, and to adjust the outer loop control reference signal in response to the changes. This requires that the retrofit control architecture contain the capability to determine the changed relationship between fan speed and thrust, and the intelligence to recognize the cause of the change in order to correct it or warn the pilot. The proposed retrofit architecture is able to determine the fan speed setting through recognition of the degradation level of the engine, and it is able to identify specific faults and warn the pilot. In the flight simulator it was demonstrated that when degradation is introduced into an engine with standard fan speed control, the pilot needs to take corrective action to maintain heading. Utilizing the intelligent retrofit control architecture, the engine thrust is automatically adjusted to its expected value, eliminating yaw without pilot intervention.

APPENDIX B: REVIEWS SUPPORTED

Below is a list of various reviews that were supported by FDAB personnel during FY2005.

New Horizons (APL) Mission Design Review
CALIPSO Delta Flight Operation Review
Interstellar Boundary Explorer (IBEX) Software Requirements Review (as Integrated Independent Review Team (IIRT) panel member)
THEMIS Mission Operations Review
HRSDM System Requirements Review
HRSDM GNC Peer Review
HRSDM Preliminary Design Review
HST One-Gyro Science Control Mode GNC Peer Review
HST Zero Gyro Kalman Filter Peer Review
Multilensing Planet Finder (MPF) Peer Review
Solar Terrestrial Relations Observatory (STEREO) Pre-Environmental Review
Solar Dynamics Observatory (SDO) Critical Design Review
NESC's Review of the Orbiter Repair Maneuver
STEREO Mission Operations Review (MOR)
VESPER Probe Peer Review
Sentinels Science and Technology Definition Team Meetings
STEREO Flight Dynamics Peer Review
Magnetospheric Multiscale (MMS) Mission Science Team Quarterly

APPENDIX C: ACRONYMS AND ABBREVIATIONS

AAS	American Astronomical Society
AC	Afternoon Constellation
ACE	Advanced Composition Explorer
ACS	Attitude Control System
ADS	Attitude Determination System
ADM	Attitude Data Messages
AETD	Applied Engineering and Technology Directorate
AIAA	American Institute of Aeronautics and Astronautics
APL	Applied Physics Laboratory
AR&C	Autonomous Rendezvous and Capture
ARC	Ames Research Center
ATV	Autonomous Transfer Vehicle
BGS	Berkeley Ground System
BSS	Boeing Satellite Systems
C_3N ConOps	Command, Control, Communications, and Navigation Concept of Operations
CA	Conjunction Assessment
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite
CCS	Constellation Coordination System
CCSDS	Consultative Committee for Space Data Systems
CDD	Capability Development Document
CDR	Critical Design Review
CI	Configuration Items
CLAIM-3D	3D Cloud Aerosol Interaction Mission
CME	Coronol Mass Ejections
CMNT	Colloidal MicroNewton Thruster
CMOC	Cheyenne Mountain Operations Center
CNE	Center Network Environment
CNES	*Centre National d'Etudes Spatiales*
CON-X	Constellation X
co-op	Cooperative Education
COS	Cosmic Origins Spectrograph
COTS	Commercial-Off-the-Shelf
CP	Conference Proceeding
CRTBP	Circular Restricted Three Body Problem
CSOC	Consolidated Space Operations Contract
CSS	Cross Support Services
dB	decibel
DART	Demonstration of Autonomous Rendezvous Technology
DCS	Dynamics Control System
delta-DOR	Delta Differential One-way Range
DFP	disturbance free payload
DM	Deorbit Module
DoD	Department of Defense
DOF	degree of freedom

DR	Dexterous Robot
DRS	Disturbance Reduction System
DSN	Deep Space Network
EACVS	Enhanced Auto-track Computer Vision System
EKF	Extended Kalman Filter
ELV	Expendable Launch Vehicle
EM	Ejection Module
EMCC	Emergency Mission Control Center
EMSD	Exploration Mission Systems Directorate
EO	Earth Observing
EOB	extended optical bench
EOC	Emergency Operation Center
EOS	Earth Observing System
EPIC	Extrasolar Planet Imager Coronagraph
ERBS	Earth Radiation Budget Experiment
ESA	European Space Agency
ESMO	Earth Sciences Mission Operations
FAST	Fast Auroral Snapshot Explorer
FB	Flight Baseline
FD	Flight Dynamics
FDAB	Flight Dynamics Analysis Branch
FDDD	Flight Design and Dynamics Division
FDF	Flight Dynamics Facility
FD&MO	Flight Dynamics and Mission Operations
FDS	Flight Dynamics System
FFT	Fast Fourier Transform
FFTB	Formation Flying Test Bed
FGS	Fine Guidance Sensors
FOT	Flight Operations Team
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	Fiscal Year
GA	Grapple Arm
GB	Green Book
GEONS	GPS-Enhanced Orbit Navigation System
GGSS	GEONS Ground Support System
GLAST	Gamma Ray Large Area Telescope
GMAN	General Maneuver Program
GMAT	Goddard Mission Analysis Tool
GMSEC	Goddard Mission Services Evolution Center
GMT	Greenwich Mean Time
GN	Ground Network
GNC	Guidance, Navigation, and Control
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRC	Glenn Research Center
GRS	Gravitational Reference Sensor

GSFC	Goddard Space Flight Center
GTDS	Goddard Trajectory Determination System
GUI	Graphical User Interface
HEO	High Earth Orbit/ Highly Elliptical Orbit
HGA	High Gain Antenna
HiFi	High Fidelity
HP	Hewlett-Packard
HQ	Headquarters
HRDI	High Resolution Doppler Imager
HRSDM	Hubble Robot Servicing and Deorbit Mission
HRV	Hubble Robotic Vehicle
HST	Hubble Space Telescope
HTV	H-II Transfer Vehicle
Hz	Hertz
ICD	Interface Control Document
IDP	Individual Development Plan
HIS	Inner Heliosphere Sentinels
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMDC	Integrated Mission Design Center
IOAG	Interagency Operations Advisory Group
IPO	Integrated Program Office
IRAS	Interspacecraft Ranging and Alarm System
ISP	In-Space Propulsion
ISS	International Space Station
IT	Ionosphere-Thermosphere/Information Technology
JAT	Java Astrodynamics Toolbox
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
km	Kilometer
L&EO	Launch and Early Orbit
LaRC	Langley Research Center
LEO	Low Earth Orbit
LF	Logistics Flight
LISA	Laser Interferometer Space Antenna
LOF	Local Oscillator Frequency
LOLA	Lunar Orbiter Laser Altimeter
LPF	LISA Path Finder
LRO	Lunar Reconnaissance Orbiter
LT	Low Thrust
LTP	LISA Test Package
m	Meters
MALTO	Mission Analysis Low Thrust Optimization

MAP	Microwave Anisotropy Probe
marcs	Milliarcsecond
MC	Morning Constellation
MD	MacDonald-Dettwiler Robotics
MESA	Mission Engineering and Analysis Branch
MESAD	Mission Engineering and Systems Analysis Division
MIB	Mishap Investigation Board
min	Minute
MLT	Mean Local Time
MMS	Magnetospheric Multiscale Mission
MMWG	Momentum Management Working Group
MOC	Mission Operations Center
MOIMS	Mission Operations and Information Management Services
MOMS	Mission Operations and Mission Services Contract
MOT	Maneuver Operations Team
MOU	Memorandum of Understanding
MOWG	Mission Operations Working Group
MSASS	Mission Spin-Stabilized Spacecraft
MSFC	Marshall Space Flight Center
MTASS	Mutli-mission Three-Axis Stabilized Spacecraft software
MTDE	Metric Tracking Data Evaluation
MUBLCOM	Multiple Paths, Beyond-Line-of-Sight Communications
NASA	National Aeronautics and Space Admnistration
NDSPO	NASA Data Standards of Program Office
NDSWG	NASA Data Standards Working Group
NESC	NASA Engineering and Safety Center
NEWB	New Employee Welcoming Board
NFIR	Natural Feature Image Recognition
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NSG	Network Support Group
OCO	Orbiting Carbon Observatory
OD	Orbit Determination
ODM	Orbit Data Messages
ODTK	Orbit Determination Tool Kit
OMG	Object Management Group
OOS	On-Orbit Staging
ORM	Orbit Repair Maneuver
ORR	Operations Readiness Review
OS	Operating System
OSC	Orbital Sciences Corporation
OTIS	Optimal Trajectory by Implicit Simulation
OTWG	Orbit Trade Working Group
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences couples with Observations from a Lidar

PCS	Pointing Control System
PD	Proportional Derivative
PDM	Propulsive Deorbit Module
PDR	Preliminary Design Review
PI	Principal Investigator
PID	Proportional Integral Derivative
PIP	Professional Intern Program
PiVoT	Position-Velocity-Time
PNT	Position, Navigation, and Timing
QA	Quality Assurance
R&D	Research and Development
RASC	Revolutionary Aerospace Systems Concepts
R_e	Earth Radius
RLEP	Robotic Lunar Exploration Project
RFA	Request for Action
RFP	Request for Proposal
RMS	Root Mean Squared
RSDO	Rapid Spacecraft Development Office
RTF	Return to Flight
RXTE	Rossi X-Ray Timing Explorer
s	second
SAC-C	*Satélíte de Aplicaciones Científícas*
SCAWG	Space Communications Architecture Working Group
SDTF	Space Data Task Force
SDO	Solar Dynamics Observatory
SEED	Systems Engineering Education Development
SEP	Solar Energetic Particles
SM4	Fourth Servicing Mission
SMEX	Small Explorer
SN	Space Network
SNAP	Simulated N-body Analysis Program
SOHO	Solar and Heliospheric Observatory
SPDM	Special Purpose Dexterous Manipulator
SPIE	International Society for Optical Engineering
SQP	Sequential Quadratic Programming
SPIRIT	Space Infrared Interferometric Telescope
SPRT	Super Problem Resolution Team
SRR	System Requirements Review
SSMO	Space Science Mission Operations
ST	Space Technology
STEREO	Solar-Terrestrial Relations Observatory
STK	Satellite Tool Kit
STP	Solar Terrestrial Probe
STS	Space Transportation System
SWAS	Submillimeter Wave Astronomy Satellite
SwRI	Southwest Research Institute
TDM	Tracking Data Messages

TDRS	Tracking and Data Relay Satellite
TDRSS	TDRS system
TFA	Trajectory Feasibility Analysis
TGS	Two-Gyro system
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Technical Interchange Meetings
TLE	Two Line Elements
TOMS	Total Ozone Mapping Spectrometer
TOMS-EP	TOMS-Earth Probe
TOPO	Trajectory Operations Officer
TPF	Terrestrial Planet Finder
TPF-C	Terrestrial Planet Finder Coronagraph
TRACE	Transition Region and Coronal Explorer
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmospheric Research Satellite
UCB	University of California, Berkeley
US STRATCOM	United States Strategic Command
USGS	United States Geological Survey
USAF	U.S. Air Force
USN	Universal Space Network
UVF	Unit Vector Filter
VSE	Vision for Space Exploration
VESPER	Venus Sounder for Planetary Exploration
WMAP	Wilkinson Microwave Anisotropy Probe
WG	Working Group
WR	Western Range
WRS-2	World Wide Reference System 2
XML	Extensible Mark-up Language
XTCE	XML Telemetric and Command Exchange

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31-08-2006

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Flight Dynamics Analysis Branch End of Fiscal Year 2005 Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Goddard Space Flight Center
Greenbelt, MD 20771

8. PERFORMING ORGANIZATION REPORT NUMBER
2006-00904-0

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING REPORT NUMBER
TM-2006-214139

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited, Subject Category: 42, 39
Report available from the NASA Center for Aerospace Information,7121 Standard Drive, Hanover, MD 21076. (301)621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2005. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based), spacecraft trajectory design and maneuver planning, attitude analysis, attitude determination and sensor calibration, and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

15. SUBJECT TERMS

Flight dynamics, spacecraft trajectory, attitude analysis, attitude determination and control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19b. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified	90	Thomas H. Stengle
					19b. TELEPHONE NUMBER ***(Include area code)*** (301) 286-5478